S100 1 and 2

THE OPEN UNIVERSITY

Science Foundation Course Units 1 and 2

# Science: Its origins, scales and limitations

# Observation and measurement

The Open University

*Science Foundation Course Unit 1*

# SCIENCE: ITS ORIGINS, SCALES AND LIMITATIONS

*Prepared by the Science Foundation Course Team*

THE OPEN UNIVERSITY PRESS

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This text is one of a series that, together, constitutes *a component part* of the Science Foundation Course. The other components are a series of television and radio programmes, home experiments and a summer school.

The course has been produced by a team, which accepts responsibility for the course as a whole and for each of its components.

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The following people acted as consultants for certain components of the course:

J. D. Beckman
H. G. Davies
D. J. Miller
J. R. Ravetz
B. S. Cox
R. J. Knight
M. W. Neil
H. Rose

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Open University courses provide a method of study for independent learners through an integrated teaching system, including textual material, radio and television programmes and short residential courses. This text is one of a series that make up the correspondence element of the Science Foundation Course.

The Open University's courses represent a new system of university level education. Much of the teaching material is still in a developmental stage. Courses and course materials are, therefore, kept continually under revision. It is intended to issue regular up-dating notes as and when the need arises, and new editions will be brought out when necessary.

1.2

# Contents

**Explanatory note**

In this and subsequent units of this Course, the preliminary pages will include:

(1) a list of scientific terms, concepts, and principles used in the unit;
(2) a conceptual diagram of the main ideas discussed in the unit;
(3) a statement of learning objectives for the unit.

These three items are also supplied in loose-leaf form, to insert in your revision binder, together with the self-assessment questions. We hope these items will help you in planning your work, in relating units one to another, and in revising during the course of the year.

The *list of objectives* is a guideline to what we hope you will learn from each unit, and an indication of what you may expect in assessment and examination material. You will find that the self-assessment questions relate to and exemplify the objectives.

The *list of scientific terms, concepts, and principles* was originally used to help prepare the Course. We believe that they can also help you in your studies and revision. The tables indicate:

(i) what you are assumed to know before you start work on the unit (columns 1 and 2);
(ii) the main terms you are expected to learn, and where they are discussed in the unit (column 3);
(iii) how the unit is related to subsequent units (column 4).

The *conceptual diagram* is a simplified interpretation of the relationships between the main ideas discussed in the unit. Each diagram should help you to visualize the whole subject matter of the unit, and to stimulate you to produce your own diagram should you think it necessary.

In the main text of the unit you will occasionally find a question that is answered in the margin. The first example of such a question is on page 13 of Unit 1. If you wish to try to answer the question without seeing the answer, just cover the margin with a suitable piece of card or paper. This is really a matter of personal preference; there is no evidence that you are likely to learn better or worse if the answer is 'hidden'.

**Table A**

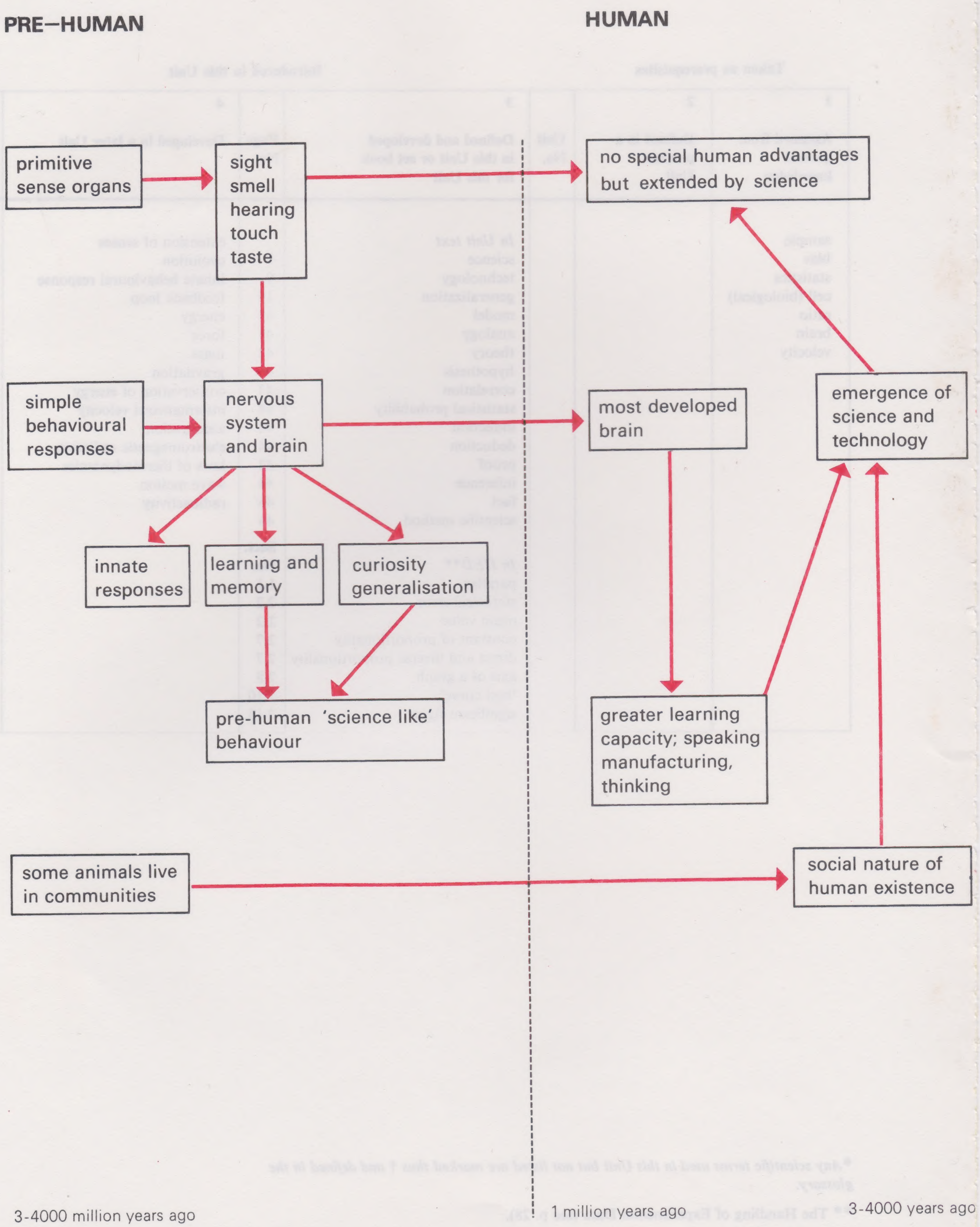
## A List of Scientific Terms, Concepts and Principles used in Unit 1*

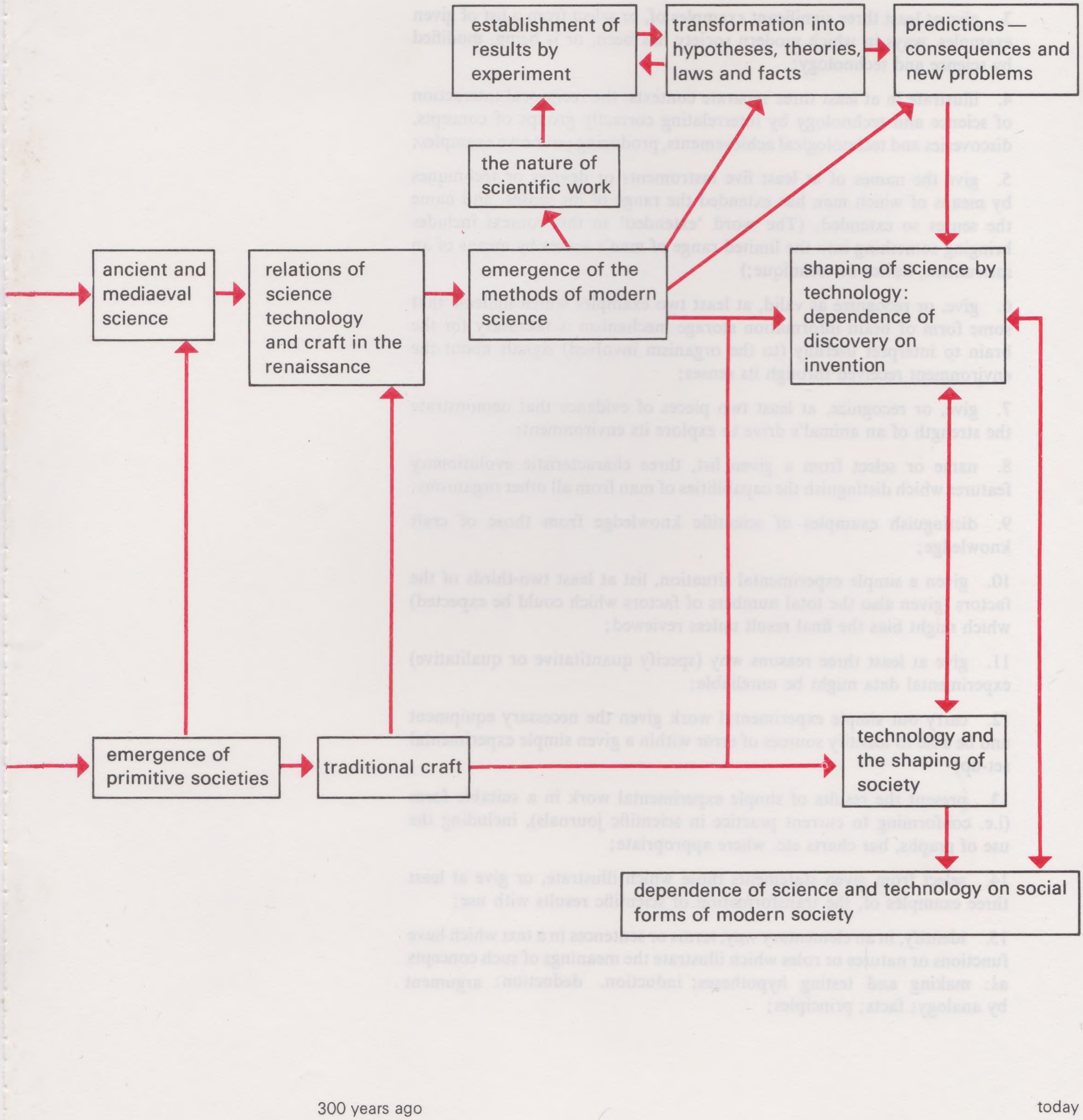
| Taken as prerequisites | | | Introduced in this Unit | | | |
|---|---|---|---|---|---|---|
| 1 | 2 | | 3 | | 4 | |
| **Assumed from general knowledge** | **Defined in a previous Unit** | **Unit No.** | **Defined and developed in this Unit or set book for this Unit** | **Page No.** | **Developed in a later Unit** | **Unit No.** |
| sample | | | *In Unit text* | | extension of senses | 2 |
| bias | | | science | 9 | evolution | 21 |
| statistics | | | technology | 9 | innate behavioural response | 20 |
| cell (biological) | | | generalization | 16 | feedback loop | 16 |
| ratio | | | model | 42 | energy | 4 |
| brain | | | analogy | 43 | force | 4 |
| velocity | | | theory | 42 | mass | 3 |
| | | | hypothesis | 43 | gravitation | 4 |
| | | | correlation | 43 | conservation of energy | 4 |
| | | | statistical probability | 44 | instantaneous velocity | 3 |
| | | | induction | 44 | acceleration | 3 |
| | | | deduction | 44 | electromagnetic radiation | 2, 28 |
| | | | proof | 42 | laws of thermodynamics | 5 |
| | | | inference | 44 | wave motion | 2, 22 |
| | | | fact | 46 | radioactivity | 6, 31 |
| | | | scientific method | 45 | | |
| | | | *In HED*** | Sect. No. | | |
| | | | parallax | 1.1 | | |
| | | | statistical error | 2.2 | | |
| | | | mean value | 2.2 | | |
| | | | constant of proportionality | 2.7 | | |
| | | | direct and inverse proportionality | 2.7 | | |
| | | | axis of a graph | 2.8 | | |
| | | | 'best curve' | 2.10 | | |
| | | | significant figure | 2.13 | | |

**Any scientific terms used in this Unit but not listed are marked thus † and defined in the glossary.*

** The Handling of Experimental Data (see p. 28).

# PROGRESS IN SCIENCE & TECHNOLOGY




establishment of results by experiment
transformation into hypotheses, theories, laws and facts
predictions — consequences and new problems
the nature of scientific work
ancient and mediaeval science
relations of science technology and craft in the renaissance
emergence of the methods of modern science
shaping of science by technology: dependence of discovery on invention
emergence of primitive societies
traditional craft
technology and the shaping of society
dependence of science and technology on social forms of modern society
300 years ago
today

## Objectives

When you have completed this course unit you should be able to:

1. define in your own words or recognize valid definitions of the terms, concepts and principles listed in column 3 of Table A (p. 5), and recognize situations implicitly involving the ideas expressed by these terms, concepts and principles;

2. give six examples of the orders of magnitude by which man's technological capabilities have increased over the last century;

3. give at least three significant examples of, or select from a list of given examples, ways in which modern society has been, or is being, modified by science and technology;

4. illustrate in at least three separate contexts, the reciprocal interaction of science and technology by interrelating correctly groups of concepts, discoveries and technological achievements, producing your own examples;

5. give the names of at least five instruments or devices or techniques by means of which man has extended the range of his senses, and name the senses so extended. (The word 'extended' in this context includes bringing something into the limited range of man's senses by means of an instrument, device or technique;)

6. give, or recognize as valid, at least two examples which indicate that some form of brain information storage mechanism is necessary for the brain to interpret usefully (to the organism involved) signals about the environment received through its senses;

7. give, or recognize, at least two pieces of evidence that demonstrate the strength of an animal's drive to explore its environment;

8. name or select from a given list, three characteristic evolutionary features which distinguish the capabilities of man from all other organisms;

9. distinguish examples of scientific knowledge from those of craft knowledge;

10. given a simple experimental situation, list at least two-thirds of the factors (given also the total numbers of factors which could be expected) which might bias the final result unless reviewed;

11. give at least three reasons why (specify quantitative or qualitative) experimental data might be unreliable;

12. carry out simple experimental work given the necessary equipment and be able to identify sources of error within a given simple experimental set-up;

13. present the results of simple experimental work in a suitable form (i.e. conforming to current practice in scientific journals), including the use of graphs, bar charts etc. where appropriate;

14. select from given statements those which illustrate, or give at least three examples of, the transformation of scientific results with use;

15. identify, in an elementary way, terms or sentences in a text which have functions or natures or roles which illustrate the meanings of such concepts as: making and testing hypotheses; induction. deduction; argument by analogy; facts; principles;

## 1.1 Science, technology and society

We live in a highly complex industrial society. For those of us—80 per cent of the population of Britain—who live in towns and suburbs, much of our lives is passed in an environment which is man-made. Even those bits which are not man-made, the grass in the park, flowers in the garden, trees along the pavement, almost seem to exist by courtesy of man. We travel to and from work in cars, buses or trains, at work handle the elaborate machinery of production, at table eat food which has been prepared and processed by the intervention of more machinery, and at leisure are at the receiving end of yet other contemporary products—television and radio, tape-recorders and record players. All this is comparatively new, for the world produced by our technology is still continuously changing. It does not resemble the world of our parents or grandparents; it will not resemble the world of our children or grandchildren. Although everyone knows about these changes in principle, we do not often stop to consider just how large they are, and how rapid they have been in industrialized societies compared with all previous changes in the history of man. Thus in the last century, industrialized societies have increased speeds of communication by a factor† of 10 000 000 ($10^7$),* speed of travel by 100 ($10^2$), speeds of handling of data by 1 000 000 ($10^6$), energy resources by 1000 ($10^3$) and explosive power of weapons by 1 000 000 ($10^6$). Perhaps no more graphic example of the speed of scientific and technological development is needed than the fact that the distance of the first powered aeroplane flight by the Wright Brothers in 1907 was less than the length of the fuselage of one of today's generation of Jumbo Jets (Fig. 1).

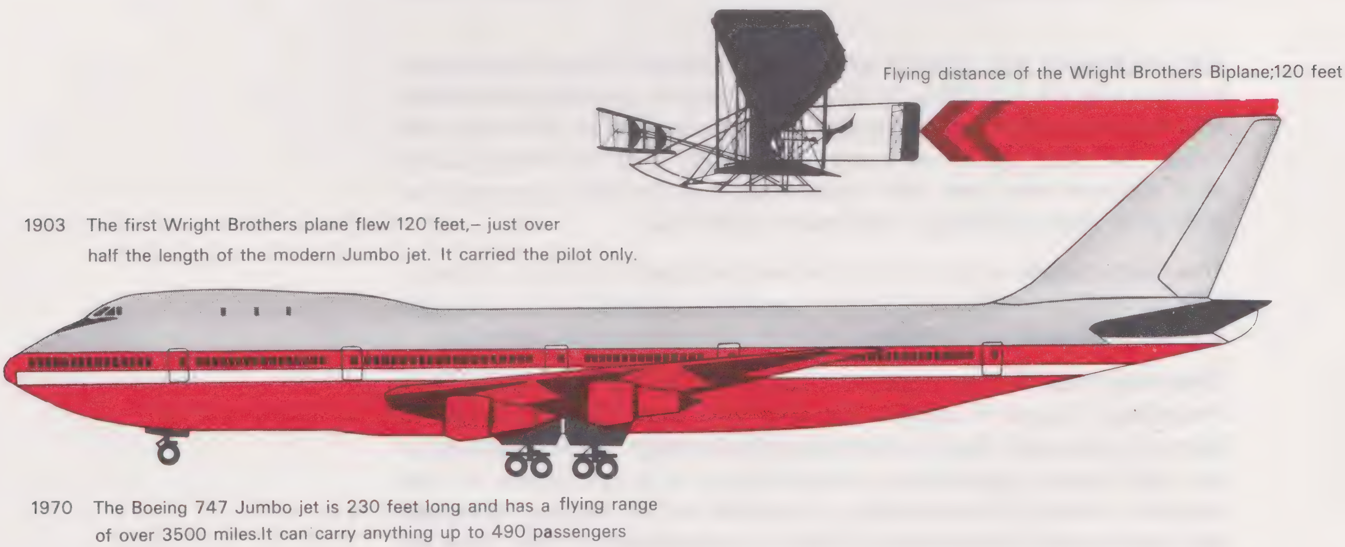



*Figure* 1

† *The meaning of terms marked thus † will be found in the glossary (p. 53).*

* *If you are unfamiliar with this way of writing numbers, an explanation of it will be found in the book* Mathematics for the Foundation Course in Science, *section 1A. This book will be referred to as* MAFS.

Because we take for granted so much of modern technology, it is difficult now to imagine what life was like only a few generations ago, before the development of today's 'technological revolution'. It is difficult to imagine how we would live if we were transported to a desert island without the products of modern technology and left to fend for ourselves. Present-day societies are held together by a set of technologies which have to some extent determined their shape—and contributed to their problems. So, too, to some extent, were earlier societies. To take but a simple example, whether a village is watered from a central well or from a drain which runs down the sides of its roads substantially determines whether the village is built in a compact central cluster or whether it is spread out in long ribbons. Whether a city is served by an effective public transport system or depends predominantly on the private car will help determine whether neighbourhoods within it are close-packed or diffuse and linked by motorways spreading amorphously into the surrounding countryside (Figs. 2a and b).

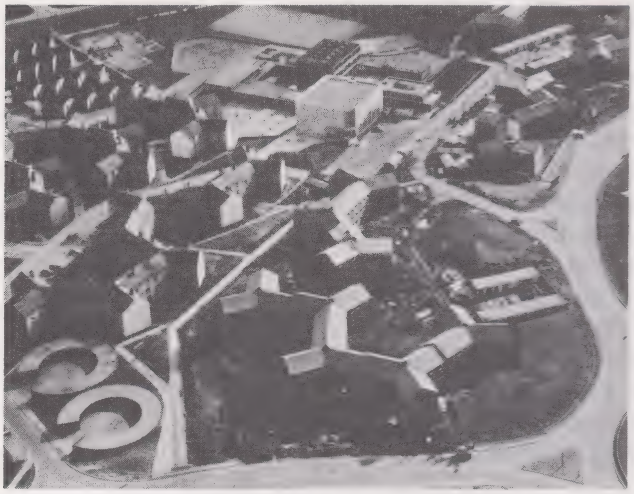


*Figure* 2a *Cumbernauld.*

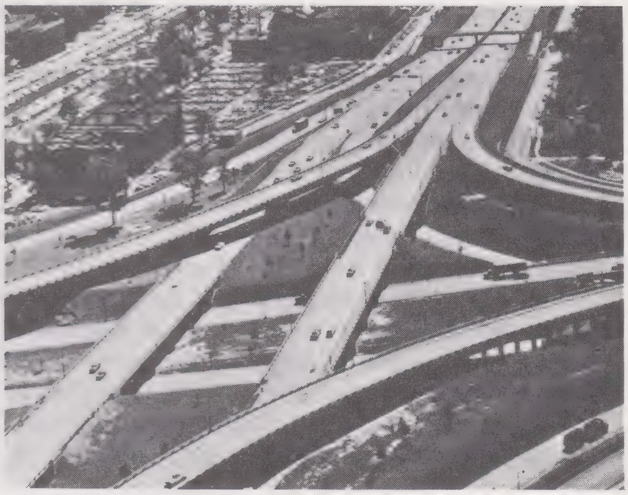


*Figure* 2b *Detroit.*

Each technology will generate quite different forms of social interaction, and choosing the technology to be applied solely on grounds of individual efficiency may well bring unintended social consequences. For those who dislike the urban sprawl of a city like Detroit, even the mixed success of a compact new town like Cumbernauld in Scotland represents an attempt to make technology serve man's preferences.

To understand our society, therefore—and understanding it is a necessity, both to survive satisfactorily within it and as a preparation for changing it where it is unsatisfactory—it is important to understand technology.

These may seem strange words with which to begin an introduction to a Foundation Course in science. Yet they have been chosen deliberately. Science is intimately linked with modern technology—some would argue that the two are indivisible—and technology is a foundation of contemporary society. The activities of scientists are an attempt to explain the natural and human world, those of technologists to use these explanations so as to manipulate this world, to use its properties in order to build new objects, machines or devices. But there is a continuity between these activities. Science traditionally may be taken to mean the advancement of our understanding of the way in which the observable world works, the development of logical, integrated and self-consistent descriptions of how and why such and such individual happenings occur, how apples fall from trees, how they appear to be coloured red and green, why they are good to eat, irrespective of the immediate usefulness of these statements. That is to say, a derivation of the laws of gravity or of optics, chemical

analysis of the constituents of the apple, or a knowledge of the physiology of digestion, is not supposed to make us immediately richer, stronger, or more able to control nature. On the other hand, the invention of the telescope, of techniques for the cooking, canning, bottling or preserving of apples, or of medicines to soothe the stomach pains we will get if we eat too many of them, are seen as technologies—they do not add to our understanding of the working of the laws of nature, but they add to our control over the world around us.

In fact, such a distinction cannot be long maintained. Telescopes were the product of a study of the properties of lenses by a Dutch spectacle-maker; but in their turn they were developed by the Italian, Galileo, for sale to the merchant traders of Venice as well as a means to study the planets. This study, in its turn, led to the discovery of the moons of Jupiter, and ultimately to evidence that the Earth revolved around the Sun and to the development of a theory of gravitation. Even the medical development of the use of magnesium hydroxide to alleviate the discomfort due to stomach acidity also led on to evidence that the stomach juices were acidic, and that their acidity was regulated by the body, ensuring efficient digestion.

So science and technology must be seen as interdependent activities; discovery precedes invention, and invention in turn makes possible discovery—at least in our contemporary society. These links between science and technology, between the methods of science and the results of science, make it difficult to agree on a single precise definition of either 'science' or 'technology'.

There are indeed at least five current uses of the word science:

(i) as the attempt to discover and explain the workings of the world of nature;
(ii) as the application of certain rules of procedure and enquiry;
(iii) as the social institutions within which these activities are carried out;
(iv) as including the whole field of research and development, that is, both science and technology as distinguished above;
(v) as excluding technological developments, embracing instead only pure scientific enquiry typically conducted in certain types of institution such as the university or basic research institute.

Remember these definitions, for we shall refer back to them subsequently.

In this Foundation Course we shall talk mainly about science in the sense of (i) or (ii). We shall be trying to describe something of the depth of understanding of the natural world which modern science has provided, from the minutest of subatomic particles to the Earth and its internal structure, and from the simplest virus to the mechanism of the human brain. This course is written by an interdisciplinary group of scientists. The different approaches of the different branches of science are reflected in the fact that each of the course units is written primarily by a specialist in that particular topic, but as a team we have tried to integrate the course and make certain general principles stand out. Thus at the same time as presenting you with the *facts* and *theories* of contemporary science, we are also trying to show you something about how a scientist goes about his business; how he makes experiments, how he happens upon theories and explanations, what he accepts as proof. We take account also of the technological and hence social application of the results of scientific research. The tremendous scientific achievements that we describe have not been made in some sort of social vacuum, unrelated to the developments in the surrounding society, and the scientist in his white lab coat is not a man apart from society. In this sense the foundations of science are also the foundations of technology—and, consequently of society. It is in making these links clear, and in attempting both to present the

panorama of modern scientific thought in a way that is broad and deep, and to show the relationships between sciences sometimes regarded as separate, like, for example, geophysics and biochemistry, that the authors of this course think that it differs from any conventional university courses in the sciences, and attempts something both new and, we think, important.

Only your experience through this course will establish how far we have succeeded.

> **As a check, write down now the reasons why you have elected to take the Foundation Course in science and three things or problems that you hope you will be able to understand at the end of it. At the end of the year, you will be able to assess how well you—and the course—have done.**

**Reasons**

**1**

**2**

**3**

**Things or problems to be understood**

**1**

**2**

**3**

## 1.2 Is human 'science' unique?

It is usual to set the emergence of 'modern science'* as occurring in Europe, in the sixteenth century and the development of science as proceeding with ever-increasing speed thereafter, particularly following the Industrial Revolution of the nineteenth century, in Britain, France and Germany, and rather later in the United States, Russia and Japan. But the activities described as science are the natural continuation of processes that had, indeed, been going on in earlier times in human societies. What is more, they are an extension of developments which we can trace not only in humans but even in the most primitive animal.

### 1.2.1 The senses and their development

The evolutionary path which has led to man and his society has been that of ever-increasing capacity to sense and react to the external world.

**Man is commonly described as having five senses. Can you name them?**

Sight, hearing, touch, taste, smell.

With these senses, primitive man must have explored the surrounding world, learned what was and what was not good to eat, what was to be feared and avoided as dangerous and what was not. Much of modern science has depended on the process of extending the range and precision of these senses, particularly those of sight, hearing and smell, making possible the detection of objects at a distance or with a degree of accuracy and clarity not otherwise possible, or of substances which would otherwise be outside the limits of detectability.

**Name some scientific devices which extend the range of each of the three senses, sight, sound or smell. (Try to name at least one instrument which corresponds to each sense.)**

Sight—telescope, microscope.
Sound—stethoscope, telephone.
Smell—breathalyser, smoke detector.

Maybe you got the first two right and not the third. The sense of smell depends on the presence in the nose of special detectors which respond, in ways we will describe in Unit 18, to small quantities of individual chemical substances in the air breathed in. The breathalyser, in measuring the amount of alcohol in breath, performs a similar job.

But the senses did not arise with man alone. More primitive animals possess them, often more fully developed than in man.

**Name some animals which have better sight, hearing or smell than man.**

You might have chosen from amongst many. For example, the ranges of sound that can be heard by the bat or the dog exceed that of man. The eyes of the owl are adapted to see quite well in a degree of darkness in

* *If you would like to read more about this, see the relevant parts of Ravetz and Bernal (Vol. 2, Chapters 7, 8 and 9). We also suggest that you read Chapters 1 to 6 of Rose and Rose over the course of the year. We shall refer to these Chapters again in Units 33 and 34. The full details of these books are given in the Book List on p. 48.*

which man cannot see at all. Not only can dogs respond to smells undetectable to the human nose, but many insects, such as bees and moths, can detect chemicals (such as the sex attractants, produced by some female moths) at concentrations so low as to be hard to detect even with the most sensitive instruments yet devised.

Man uses his senses to acquire information about his environment, particularly as to food and danger, a characteristic he shares in common with all other animals. Even the simplest one-celled creatures can react to their environment. (If you do not know in general terms that all living organisms are built up from units known as *cells*, there is no need to worry unduly here; you will learn about them in Unit 14.) Put an obstacle in the way even of a minute one-celled organism and it will move around it; put a drop of the corrosive substance sulphuric acid in the middle of a dish containing the creatures and they will move away from it. Similarly such organisms will move towards concentrations of foodstuffs or towards or away from a source of light. Such reactions to obstacles and to food are the primitive versions of the senses known in man as touch and taste or smell. A sense of temperature, that is of hot and cold, seems likely to have evolved at about the same time as these other fundamental senses. But perhaps the most significant evolutionary development was that of vision which, in evolutionary terms, probably developed quite early. The simplest present-day animals to possess a rudimentary form of vision are the little pond creatures known as flat worms. Visual patterns can be interpreted not just in terms of generalized responses at the surface of the organism, but in terms of the world of distant objects. But for this to be done, the eye must be accompanied by a *brain* capable of interpreting a complex set of stimuli. Conversely, since no other sensory organ in an animal provides such a wealth of information it is likely that the development of the human brain was linked to that of the eye.

What may have happened is that the primitive light sense shown by the one-celled animal became specialized in more complex organisms. Certain regions and groups of cells became especially sensitive to light. The visual sense probably developed from a response to moving shadows on the surface of the skin, which would have given warning of nearby danger, to recognition of patterns, when eyes developed optical systems. The stages seem to have been first a concentration of specially light-sensitive cells located at certain regions of the organism, and then 'eye-pits' with the light sensitive cells with pigmented cells round them forming the bottom of the pits. These pits gradually deepened in more advanced organisms, serving to increase the contrast of shadows in the light sensitive region by shielding them from surrounding strong light. The lens of the eye most probably started as a transparent window, protecting the eye-pits from being blocked by small particles floating in the sea in which primitive organisms lived.The protective windows may have gradually thickened at their centres, for this would have increased the intensity of light on the sensitive cells, until the central thickening became a *lens*, producing an image-forming eye, which could present optical patterns to the primitive touch-sensitive nervous system (you will learn more of the properties of such lenses in Unit 2 and of the evolution of organisms in Unit 21).

From the point in time when eyes (and ears) developed, together with the brains to process the information they provided, one road of evolutionary success lay in the development of more accurate senses and more powerful brains. Sight and hearing enabled information arriving at the organism from a distance to be processed, analysed and acted upon, giving warning of the future, enabling predators to see and hear their prey—and prey to see and hear their predators.

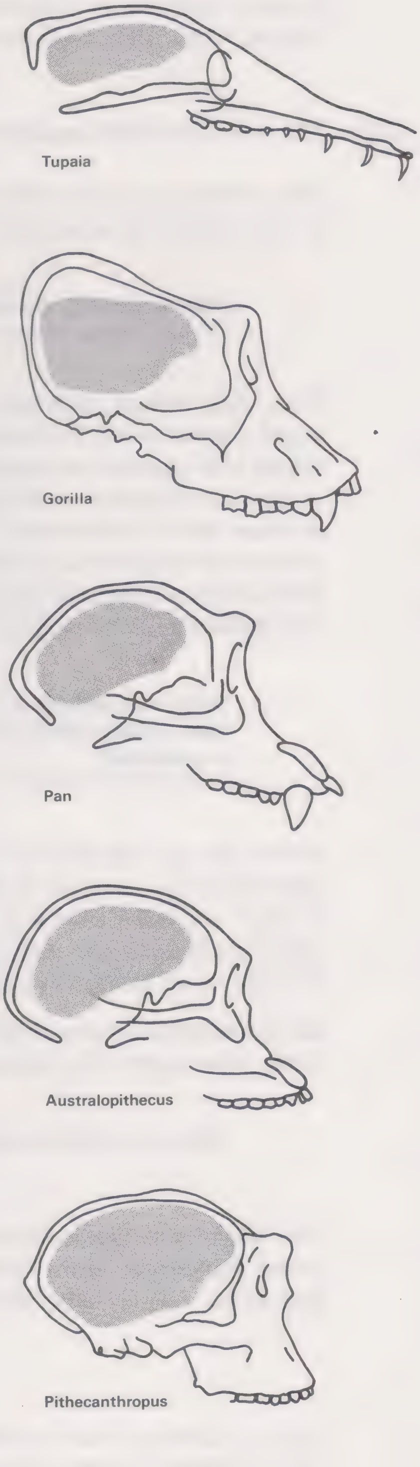
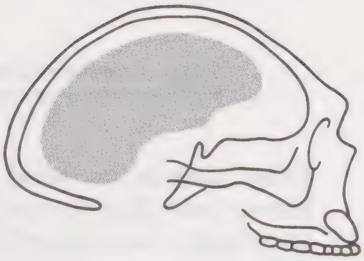


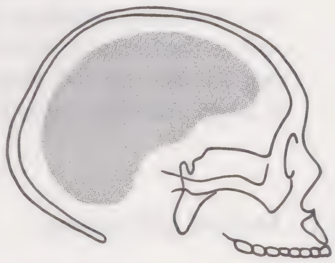

*Figure* 3

### 1.2.2 The development of the brain

The development of the senses has not been the only pathway to success in the evolution of life—plants, for instance, have developed along a different route—but for the animal kingdom it has been amongst the major ones. You will be learning in Unit 2 how one section of science is based on this development of the senses, and their extension by means of instruments and other sophisticated measuring and transforming devices that enable men to see the otherwise unseeable, hear the unhearable, smell the unsmellable, and thus enlarge their *understanding of* (i.e. science) and *power over* (i.e. technology) the external world. These extensions are in a way analogous to the extensions of our senses provided by the arts, for instance by pictures or music. These, too, in a way extend our knowledge of the world external to man, and hence our understanding of man's relationships with the world.



Homo erectus



Homo sapiens

*Figure* 3 (*cont.*)

With increased powers of sensing the environment come increased possibilities of doing something about it. The fully developed brain not only interprets the data received by way of the senses; it also decides on action to be taken and then signals to other parts of the body to make the appropriate responses. Simple signalling systems exist even in primitive animals. Even in one-celled animals there are methods for one end of the animal to keep the other end posted as to events in its environment. In many-celled animals the signalling system became more elaborate and specialized signalling cells, nerve cells, evolved. Parallel with the development of eyes, groups of nerve cells accumulated towards the front end (the end with the eyes) of the creature to form a simple brain, which became responsible for receiving the information from the eyes and other senses and processing it. The evolutionary pathway that has led to man has been one of steadily increasing brain complexity, size and number of component units (cells). Some of this development can be seen in Figure 3.

**Table 1**

**Brain and body weights and brain cell numbers in some mammals**

| Animal | Brain weight (kg) | Body weight (kg) | Approx. number of brain cells 'available for learning' (in millions) | Brain/Body weight ratio | Million brain cells per kg body weight |
|---|---|---|---|---|---|
| Rat | 0.002 | 0.300 | 20 | 0.007 | 67 |
| Elephant | 6.00 | 7 000 | 18 000 | 0.001 | 3 |
| Dolphin | 1.75 | 150 | 10 000 | 0.012 | 67 |
| Gorilla | 0.60 | 250 | 3 600 | 0.002 | 14 |
| Chimpanzee | 0.40 | 45 | 3 400 | 0.009 | 75 |
| Baboon | 0.20 | 20 | 2 100 | 0.010 | 105 |
| Macaque monkey | 0.10 | 10 | 1 200 | 0.010 | 120 |
| *Homo Erectus* | 0.90 | 50 | not known | 0.018 | — |
| *Homo Sapiens* (man) | 1.30 | 60 | 8 500 | 0.022 | 146 |

Table 1 compares a number of different mammals, including various apes and one of the immediate evolutionary ancestors of man, known as *Homo erectus*, as well as man, *Homo sapiens*, himself. It shows brain and body weights and the number of brain cells involved in learning processes, and then a calculation of two ratios, those of brain weight to body weight, and of number of brain cells per kilogram of body weight. (The figures for the extinct human ancestors are estimates based on measurements of skull

size.) Study the table carefully, particularly if you are not familiar with extracting information from such tables, then answer the question:

**Which of the features listed are greatest in man?**

The ratio of the brain cell number to body weight, and of brain weight to body weight.

Several animals, including both the elephant and the dolphin, have a heavier brain than does man; but compared on the basis of a 'standard' body weight, the elephant's brain is smaller even than the rat's, whilst the dolphin's is relatively greater than that of some of the apes. Expressed like this, man's brain weight and brain cell number is higher than that of any preceding mammal, or other animal yet examined. The number of cells in the human brain which are 'free' for thinking, learning, remembering, etc. and are not committed to particular stereotyped body functions is larger than that of any other animal.

### 1.2.3 Memory and learning

In order that the brain may signal an appropriate response to information received about a situation, it must be able to *compare* this present information with other material which in the past resembled it. Is the noise arriving at the ears that of an enemy or possibly of prey? Is the shape and pattern observed by the eyes that of friend or foe? To answer these questions it is necessary to know whether similar noises and shapes in the past have been those of predator or prey, friend or foe, and to compare the present ones with the past. This comparative procedure is that of memory, and even *apparently* quite simple animals show memory and can learn. Insects such as bees can remember quite complex 'maps' of how to get from their hives to food and back again. Snails and some insects show certain types of learning. Thus if a snail receives an electric shock every time it extends its eye stalk, it will learn not to do so; if an octopus receives a crab for food every time a white square is shown at the same time, but an electric shock when the crab is presented at the same time as a black square, the octopus will learn not to approach the crab when the black square is shown. Even cockroaches can be trained to fold their legs so as to avoid getting an electric shock. More complex organisms, such as pigeons and other birds, can be taught to count (up to 4 or 5 at any rate) for reward of food, whilst rats can be trained to traverse quite complex mazes, press levers for food and distinguish between circles, squares and other shapes. Any such relatively crude tests of memory and learning that can be studied by the scientist in his laboratory are elementary feats by comparison with those achieved by animals in their everyday lives. An insect-eating bird needs to remember not only that 'flies taste good' but also that 'yellow and black striped flies taste bad'. This is the procedure of making *generalizations* about the world; 'if one (or two or three) yellow and black fly tastes nasty and is dangerous, then *all* may well do'. Thus the animal develops a set of behaviour patterns (or rules) for ordering and arranging the universe around it. (However, such rules can lead to mistakes being made. Some good-tasting insects have also developed yellow and black striped colouring and so survive better because they appear to be dangerous.)

Some of these rules of procedure have apparently become, during the course of evolution, *innate*, that is inherited or inborn. The baby birds of certain species open their mouths when they see their parent, and thus can receive food; they will do this, even when hatched and reared in isolation and fed by hand, whenever they are shown even a crude 'beak' shape, provided it is coloured appropriately. Other species respond to the shadow of a hawk-like shape by cringing or seeking shelter, even when

they have been reared from birth under conditions in which they could not possibly ever have seen a bird of prey. Such behavioural responses are thus built into the animal (you will read more about them in Unit 20).

### 1.2.4 'Exploratory' behaviour

But whilst these responses are perhaps so important for survival that they seem inflexible to the outside observer, some species, particularly along the evolutionary path that has led to man, also show a considerable degree of flexibility in response, enabling the animal to adapt itself and learn to survive under changing conditions in the external world. Perhaps this flexibility is best shown by the powerful 'drive' which exists in some animals towards 'exploratory' behaviour. For instance, if a rat is made hungry and thirsty by depriving it of food and water for 24 hours, and then both are put into its cage, it will immediately both eat and drink. But if instead of the food and water being placed in the rat's own cage, it is taken out of its cage and placed in a fresh one where there is food and water, it will *not* eat and drink immediately. Instead, it will roam up and down the new cage, sniffing at it, apparently examining it and exploring it from many angles. Only later will it turn to the food and water, and satisfy hunger and thirst. The rat behaves as if its 'drive' to explore a new and unfamiliar situation is even more powerful than that to eat and drink.

Although one must beware of making analogies between the behaviour of rats and that of humans (such a tendency verges upon *anthropomorphism*—investing a non-human thing with human characteristics, a tendency often displayed by doting dog-owners), one can cautiously ask the question:

**What behaviour pattern in humans would you say would be similar to that shown by the rat?**

Curiosity.

Such 'curiosity-like' behaviour is shown in species of the mammalian evolutionary line which leads to man.

An even more striking example is that rats will behave as if they are adopting and testing simple strategies and hypotheses. In one group of experiments, made in California in 1935, rats were shown a series of closed doors under each of which a light could be switched on. Only one light was switched on at a time, and all the doors except one were locked. The rat had to jump at a door: if it was unlocked he could get through and was rewarded with food. The only clue as to which was the unlocked door was the position of the light. It could be the door above the light, or the one to the right, or in any other relation. In this situation the behaviour of the rats could only be interpreted (by humans) as if the rats were testing their own 'hypotheses', for instance, the hypothesis that the unlocked door was the one to the right of the light whenever the light appeared. If after several trials they failed, they would try another hypothesis until they hit on the right one. The point of the experiment was that the rats did not try just any combination of doors and lights, they worked through and 'tested' particular 'hypotheses' quite systematically.

Even more clearly explorative behaviour is shown in the animal species closest to man, such as the apes. During the First World War, a famous series of experiments was conducted by the German psychologist Wolfgang Köhler in which he placed a chimpanzee in a cage with a bunch of bananas just outside. The animal soon learned to reach outside the cage for the bunch. Köhler then put the bunch of bananas further from the cage, so that it could not be reached by the monkey simply stretching out its hand. But he put a stick in the cage. After failing to reach the bananas with its

hands, the animal eventually picked up the stick, poked it through the bars of the cage and hooked the bananas with the end of it. In the next experiment, the bananas were still further from the cage, out of reach of hand or stick, but inside the cage were not one but two short sticks, which could be slotted together to make a longer one. In what was perhaps the most famous experiment of the series, Köhler's ape, after trying and failing to reach the bananas with the short stick, finally 'hit upon' the possibility of slotting them together and immediately succeeded in dragging the bananas to himself. In a primitive sort of way Köhler's ape, by making a 'creative synthesis' in order to bring about a desired result and solve a particular problem, was performing that class of activity which one might regard as characteristically human and particularly 'scientific'.

### 1.2.5 Generalization

Another type of human behaviour which could be regarded as 'scientific' (in the sense of definitions (i) and (ii) on p. 11) is also shown by other animals. This is the capacity to generalize. If a chimpanzee is set a problem in which he is presented with a row of cubes, under the third of which there is a peanut, he will eventually learn to look without error under the third cube for the peanut. If the cubes are replaced by some other shape, say pyramids, the animal will once more learn that the peanut is to be found under the third, and by the time the pyramids have been replaced by yet other shapes of objects the animals will learn to generalize, that whatever the object, the peanut is always under the third in line. This process of *generalization* is very much what one part of science is about (it is an example of *induction*, see p. 44).

What we have tried to show so far is that, although the activities described as 'science' are unique to man, there are in the animal world a whole series of activities in which the primitive analogies to modern scientific activity can be recognized. Human science and technology, which have produced relativity theory and the understanding of the genetic code, penicillin and hydrogen bombs, may seem far removed from such pre-human examples, yet they are clearly related.

Of this particular evolutionary line, of increasing brain power, increasing power of analysis, exploration, learning and manipulation, man has so far been the outstanding end-product. The arrival of man on the world scene meant the coming of an animal which in at least three major respects was immensely more accomplished than any predecessor.

**Suggest which these might be.**

Ability to think.
Ability to speak.
Ability to make tools.

### 1.2.6 Tools

The last of these accomplishments is the easiest to understand. Human hands are different even from those of man's nearest evolutionary neighbours, particularly in the position and manoeuverability of the thumb. Compare, for example, Figures 4a and b. Human thumbs can be swivelled into a variety of positions relative to the fingers impossible even for chimpanzees. This makes holding and adjusting things possible, makes fine control of delicate objects feasible, and in its turn leads to the possibility of manufacturing hand-extensions, i.e. tools far removed in complexity and ingenuity from the sticks, stones and leaves used by several kinds of ape. In addition, man, unlike the apes, can stand upright on two legs without the need to use his hands to help with balancing. This frees his hands for other functions. The gap between the contemporary tape- and computer-controlled machine tool, and the hand-chipped flint axe is less,

perhaps, than that between man's flints and anything that had gone before. The development of tools, in the sense of extensions to man's hand, and instruments in the sense of extension to his senses, thus characterize man's emergence as *Homo sapiens*. However, the use, and to an even greater degree the development, of tools is not really possible for a man in isolation, but depends upon the social nature of humans, the fact that they live in communities.

*Figure* 4a

*Figure* 4b

### 1.2.7 Speech

The second major feature to arrive with man is the power of speech. Not even the most advanced of apes has this capacity. Certainly many animals can signal quite complex messages to each other. Bees can signal not only the presence but also the direction and approximate distance of nectar. Birds can inform one another whether they are paired or single, whether one bird is a trespasser on another's territory, and so forth. Distress, danger and sexual willingness can be signalled by many animals. Dolphins can apparently communicate by sound signals. But only man has the ability to represent the steps of an argument or to relate a sequence of events by means of an ordered sequence of spoken or written signs.

**It is often said that parrots, budgerigars and some other birds can speak. Is this true?**

No—such birds can imitate sounds that they can hear, and can often do this with striking accuracy, but there is no suggestion that they can use the sound to signal meaning or ideas, or to communicate the content symbolized by the sounds.

Nor can any animal draw object-like pictures. Although some apes will paint rather unstructured patterns, they are never recognizable pictures of objects. The earliest of these are the cave paintings of man (compare Figs. 5a, b, and c for instance, pp. 20 f.).

Much effort has been expended in trying to teach apes to talk, and it is not altogether clear why they cannot. In 1969 an experiment was described in which a chimpanzee was reared from birth in the home of an experimental psychologist who claimed to have been able to teach the animal a sign language of a 'few dozen' words, similar to those used in communicating with the deaf-and-dumb. But interesting as such experiments are, it is unlikely that the chimpanzee will ever advance beyond the vocabulary of a human child of one or two. There are some suggestions that dolphins can communicate both with each other and with humans, but once again, the extent of this communication is very limited. Communication by speech is unique to the human species.

Speech made possible the transfer of experience between individuals, and

*Figure 5a Cave painting.*

*Figure 5b Picture by a six-year-old child.*

*Figure 5c Picture by a chimpanzee.*

the subsequent development of written communication systems extended this transference to individuals who might be distant from one another in space or in time. Thus, instead of having laboriously to assemble a 'map of the world' from scratch with perhaps a few innate and stereotyped rules, like those of recognition of 'mother' and 'danger' we described earlier for birds, each generation of man has been able to build upon the experience of those which came before. A discovery once made could be recorded, elaborated upon and improved, a process itself speeded up by the development first of writing, then printing, and more recently of film, tape and computer.

Such stores of knowledge, experience and new data represent extensions of man's brain capacity, that is, of his ability to think, which we noted above as the most important new feature which distinguishes man from his evolutionary forbears. Even without them he could carry in his head vastly more information than could other animals as a result of the more complex structure of his brain. With the addition of these new extensions, as we pointed out at the very beginning of this Unit, his communication and handling of data can be speeded by factors of a million or more. It is therefore by cashing in on and exploiting the three evolutionary advantages with which he started (those of brain, speech and tools), that man owes his present evolutionary success. Science and technology represent the systematic exploitation of these advantages.

## 1.3 The birth of science

With the appearance of the distinctly human powers of thought, speech and tool-making, the evolutionary development of man took a new turn: from *biological* to *social*. Although other species of animals have sensory equipment and skills that are quite impressive, and which often exceed their counterparts in humans, all the evidence indicates that the range of abilities for each species is fixed. The experience of one generation cannot modify substantially the behaviour of the next. Certain animals have been capable of being 'tamed' and of interacting with their human hosts in a very sophisticated way, but a twentieth-century cat probably has no greater range of skills than one that the ancient Egyptians worshipped. By contrast, within the limits of its genetic constitution, the human species has been adding to its stock of knowledge and skills at a constantly increasing rate.

Some of the crucial inventions that brought human life further and further from that of the animals are well known: the use of fire; the control of domestic animals by, for instance, the invention of the bridle and stirrup; the invention of the wheel; the manufacture of cutting tools and weapons; pottery; agriculture; smelting and alloying of metal. There were doubtless many others, from earliest times, of which no material trace remains. As new inventions were *achieved* and *retained* through successive generations, social life itself was transformed. Hunters preying on animals became herdsmen and stock-breeders; people living in a more settled way, gathering edible fruits and grasses, became farmers; and the possibilities inherent in a settled society with a social division of labour were realized in the great urban civilizations of Egypt, Mesopotamia, India and China.

In the achievement and transmission of these basic techniques, there was an element of 'science' present. For the attempts at the *understanding, prediction and control* of nature went hand in hand. Moreover, each of these tasks involved, in its own way, a direct contact with the uncontrolled world of nature. The regularities of the natural world, the cycle of the seasons and the Moon, the rising and setting of the Sun, the revolutions of the stars in the heavens, were important for huntsman and farmer alike. Irregular phenomena, usually natural disasters such as floods and earthquakes, storms and drought ('acts of God', as they are still called in a Householder's Comprehensive Insurance Policy) but also strange occurrences like eclipses and rainbows, called for an understanding of their causes, and, if possible, prediction. And since men then believed that all these events (the regular and the irregular) were caused by personal agents (gods) who needed to be honoured and pleased, there was no sharp distinction between religion, magic, technology, and 'science'.

Quite late in human social evolution there developed what has become known as 'pure science': the quest for knowledge for its own sake. This has been called the 'Greek miracle' of the fifth century B.C. In that period were established the ideas of mathematics as a system of *deductive knowledge* rather than a technique for measuring and reckoning; of philosophy as an enquiry into the nature of human knowledge; and of the explanation of natural phenomena independently of myths and magic. Certain sciences were found to be capable of systematic development as coherent bodies of knowledge, and in the following centuries grew to be independent of their roots in ancient craft practice. Perhaps the first was mathematics. There followed the emergence of astronomy as distinct from astrology; of anatomy and physiology from practical medicine; and botany from pharmacy and agriculture. But these developments were long and uneven. The ideal of 'pure science' did not get firmly established

until nearly the nineteenth century; and even today there are more people in the United States—and perhaps in Britain—earning a living from astrology than from astronomy!

Even after the birth of 'science' as modern men understand it, technology and the practical crafts were at first only slowly and patchily affected by science, but continued to evolve in response to their own needs and possibilities. For knowledge of the *causes* of natural phenomena was until recent times too limited (and usually too unreliable!) to guide the process of invention of new means of controlling their *effects*. Even in China, where there was a long tradition of sophisticated technology and of enquiry into the natural world, scientific research as we understand it never got under way. And in other societies such as those of Ceylon and Mesopotamia quite elaborate systems of waterworks could be invented and operated in the absence of 'science'. Through many centuries, and in all civilizations, there tended to be a division of labour: the causes of natural events were studied from books and was an occupation for the educated scholar; while control of effects was left to the artisan, who got his hands dirty, and was considered to need little, if any, literacy. This social division was clearly marked in medicine in Europe: the university-trained physician would diagnose and prescribe on the basis of the patient's horoscope and by examination of the colour of his urine (this practice is typified by the Doctor of Physick in Chaucer's *Canterbury Tales*), while the barber-surgeon performed particular operations learned as craft secrets from a master.

### 1.3.1 The Renaissance

The unification of 'science' and 'arts', 'craft' and 'technology' began to take place in Europe during the Renaissance in the fifteenth and sixteenth centuries. An increasing range of crafts received the attention of learned men (navigation, warfare, mining, surgery) and scholars gradually came to use and value craft experience, to develop the idea of making *controlled experiments*. It was at this time, too, that the sort of 'science' with which we are now familiar began to emerge out of this contact and mutual enrichment between the work of scholars, craftsmen and artists. By the beginning of the seventeenth century, work which has become a permanent part of our accepted scientific knowledge, such as, in England, Gilbert's discovery of terrestrial magnetism and Harvey's discovery of the circulation of the blood and, in Italy, Galileo's discovery of the laws governing the motion of falling bodies, was appearing.

Very soon there was established an approach to enquiry in the natural world which we can see as 'science', in many of the senses defined on p. 11.

**Do you recall the definitions of 'science' we adopted there?**

If not, check back!

In this new sort of science, there was a much closer relationship with technology: from industrial (or military) practice would come ideas for problems and techniques and instruments; and when solutions were achieved, every attempt would be made to turn them to profitable use.* By the middle of the seventeenth century, the methods of science as we

* *We have not time here to trace the history of subsequent scientific developments. For further reading on this point, see Bernal,* Science in History, *Chapter 7, and Rose and Rose, Chapters 1–6.*

now know them were beginning to be formulated explicitly, although its social organization was to undergo further changes. From then onwards, the accepted approach to the study of nature was based on controlled experience (systematic observation or experiment), in conjunction with careful argument, for the deriving of conclusions about the behaviour of the natural world; and such results of research were submitted to the community of scientists for their assessment and use. In its results and in its methods, modern science represents the highest point yet reached in the development of man's cognitive faculties. Although science will doubtless evolve further in directions we cannot predict, and to the outsider does not seem to involve the 'affective' domain of emotion and imagination, it defines and moulds our civilization and ourselves.

## 1.4 Scientific knowledge and craft knowledge; an experiment

Even in this modern technological age, we find ourselves using, in our ordinary lives, craft skills that are learned by imitation and practice, and we do this even for the operation of equipment which depends on science for its design and production. One example is driving a car; one needs to know almost nothing about the principles of an internal combustion engine to do this successfully in ordinary use. Another example is doing household electrical jobs: but here the handyman must know something about electricity if he is not to make disastrous mistakes.

Before going on to consider the differences between craft knowledge and scientific knowledge, we want you to try an experiment, for there is no better way of learning about science than to be involved in solving a specific problem. In particular we want you to repeat one of the most famous experiments in the history of science. In it, you will see the relationships between craft and scientific skills demonstrated. The experiment was done by the great Italian scientist Galileo Galilei, who lived from 1564 to 1642 and whose work led to the discovery of the laws governing the movement of bodies and to the demonstration that the Earth moved round the Sun. Galileo invented many instruments; he pioneered the telescope, for example, and his work led him into conflict with the Catholic Church of his time, and to a famous and epoch-making dispute between scientific truth and established authority whose echoes still ring today. He is often erroneously credited with having refuted Aristotle's views on the laws of motion by dropping two weights from the leaning Tower of Pisa. The reality may have been less dramatic, but was certainly more interesting. When Galileo began his experiments, there was almost complete confusion in people's minds about such concepts as force, motion, velocity and acceleration. Galileo helped clarify these concepts (it was left to Isaac Newton finally to produce the mathematical definitions of gravity and of force and motion that were to serve as fixed points of scientific reference for over 200 years, until Einstein's formulation of relativity theory at the beginning of the twentieth century). But Galileo did more than just design ingenious experiments. More almost than any other man he developed experimental method and procedure, ushering in a new era in human thought—that of systematic science. In following his experiment, you will yourself see and feel this procedure in operation. You will also encounter another aspect of science. For, as you will discover, even great scientists can make mistakes!

### 1.4.1 Galileo's inclined-plane experiment

In this experiment, made in the first years of the seventeenth century, Galileo established experimentally that the distance travelled by a descending body increases in proportion to the square of the time that has elapsed. Most schoolboys who have studied physics have 'confirmed' Galileo's results by doing the experiment themselves. You may well wonder why this new science course of the Open University should start with such an old, standard and 'hackneyed' experiment. We have chosen it deliberately; for in many ways this experiment can illustrate more about scientific research and scientific method than the most complicated and exciting modern apparatus.

First, this is not the version of 'Galileo's experiment' demonstrated in schools. The inclined-plane experiments that are designed for schools' use are constructed to be foolproof, or 'student-proof'. They enable the

unskilled student to get accurate results, and relieve him of the necessity of grappling with the conceptual and practical problems that Galileo had. They are descended from Galileo's own experiments, but until now, to our knowledge, no science course has attempted to teach the experiment as nearly as possible to the way in which Galileo did it himself.

Even when it is done in Galileo's own way, the experiment is simple. There is not much equipment involved, and the measurements are straightforward. Hence you should have little difficulty in seeing what *ought* to be happening; and we will have more time available for discussing difficulties in the experiment itself and the problems of significance.

In the discussion you will learn some things about the experiment that may be surprising. For the experiment has, for many years, been considered as something very simple and obvious; so simple that it needed no 'hypotheses' for its design, and no 'theory' for its interpretation. After all, if one wants to know how bodies increase their speed as they fall, what is more natural than to let them drop and see what happens? Galileo's only merit was that he was one of the first people to approach the problem in a scientific way, rather than trying to find the answer in the then 2000-year-old writings of Aristotle. And this famous example has given the impression that the first steps in any science are simple experiments, free from theory, out of which quantitative laws are derived.

We want you to try the experiment first before talking about it too much; but you can immediately notice one feature of it that makes it not quite the obvious solution to the problem. Galileo was concerned with the behaviour of falling bodies and with the relationship between the time of descent and the speed at the end of the descent. This was a problem of great philosophical and scientific interest in his time; and later his law of *falling* bodies was generalized by Isaac Newton to form the theory of universal gravitation, which in turn became the foundation of celestial mechanics, and of astronautics. But if you look at the experiment, you will see that the bodies are not made to *fall*, but to *roll*. This, as you will see later, is a crucial difference. It is clear today and it was clear to Galileo that there are important differences. And so this experiment, by itself, does not give us a certain answer to the problem of the behaviour of falling bodies. Hence Galileo needed other experimental results, which we will explore later.

### 1.4.2 How Galileo described the first part of his experiment

Let us now read how Galileo described the experiment:

> A piece of wooden moulding or scantling, about 12 cubits long [*Note*: 1 Florentine cubit was about 0.6 metres, so the total length of the piece was about 7 metres], half a cubit wide, and three finger-breadths thick, was taken; on its edge was cut a channel a little more than one finger in breadth; having made this groove very straight, smooth, and polished, and having lined it with parchment, also as smooth and polished as possible, we rolled along it a hard, smooth, and very round bronze ball. Having placed this board in a sloping position, by lifting one end some one or two cubits above the other, we rolled the ball, as I was just saying, along the channel, noting, in a manner presently to be described, the time required to make the descent. We repeated this experiment more than once in order to measure the time with an accuracy such that the deviation between two observations never exceeded one-tenth of a pulse beat.

(*Note:* Galileo here reports sound experimental practice, that of making sure that the equipment is working consistently, before proceeding to try variations on the experiment. His report of agreement to within one-tenth of a pulse beat sounds exaggerated, and may well have been so. His time-measuring device was probably capable of such precision, as we shall see below; and once he got 'in tune' with the apparatus, he may well have achieved that sort of accuracy.)

> Having performed this operation and assured ourselves of its reliability, we now rolled the ball only one-quarter the length of the channel; and having measured the time of its descent, we found it precisely one-half of the former. Next we tried other distances, comparing the time for the whole length with that for the half, or with that for two-thirds, or three-fourths, or indeed for any other fraction; in such experiments, repeated a full hundred times, we always found that the spaces traversed were to each other as the squares of the times, and this was true for all inclinations of the plane, i.e. the channel, along which we rolled the ball.

(*Note:* He repeated readings in order to get reliable results. This is also an example of good experimental technique.)

> We also observed that the times of descent, for various inclinations of the plane, bore to one another precisely that ratio which, as we shall see later, the Author had predicted and demonstrated for them.

(*Note:* This passage describes quite a different experiment, which, as we shall see, was quite crucial to Galileo.)

> For the measurement of time, we employed a large vessel of water placed in an elevated position; to the bottom of this vessel was soldered a pipe of small diameter giving a thin jet of water, which we collected in a small glass during the time of each descent, whether for the whole length of the channel or for a part of its length; the water thus collected was weighed, after each descent, on a very accurate balance; the differences and ratios of the times were measured, and this with such accuracy that although the operation was repeated many, many times, there was no appreciable discrepancy in the results.

(*Note:* This bit of experimental technique is a good example of Galileo's genius at precision instrumentation. Although there were clocks in his time, they were not designed for the accurate measurement of small intervals of time; and even the pendulum, whose use was developed by Galileo, could not give sufficient precision. Knowing that weight could be measured to a greater precision than any other physical quantity, Galileo devised this method of 'weighing the time'.)

On the question of accuracy, we can calculate that the rolling ball would take about five seconds for a full descent; and 'one-tenth of a pulse beat' would be about a hundredth of that. If Galileo's 'pipe of small diameter' discharged at 25 $cm^3\ s^{-1}$*, a full run would produce water weighing some 125 g. This would need to be weighed accurately to, say, 0.5 g; and the scales for this would be in use among goldsmiths (whose trade Galileo knew very well: his most famous argument was published as *Il saggiatore* —'he who weighs the evidence'). Hence the largest source of inaccuracy would be the timing of the start and finish of the descent. So any improvement of Galileo's apparatus was not likely to improve the accuracy of the experiment.

### 1.4.3 The first experiment: what you have to do

You cannot reproduce Galileo's experiment exactly; it would be difficult to set up a track of the same size, and measuring many time intervals by weighing is time-consuming and tedious. But we hope that you have a table more than a metre long, which you can raise at one end. You have been provided with a stopwatch and a ball. The question of how much to raise the end of the table to get a suitable tilt is an example of experimental design.

**What are the disadvantages of making it too steep, or too flat?**

Too steep: the ball rolls too quickly and is difficult to time, also a strain is exerted on the table legs.
Too flat: the ball's descent may be affected by roughness in the surface of the table.

**that is, cubic centimetres per second*

Arrange for the gradient to be such that it takes about 2 to 4 seconds for a ball to roll the full distance of about 1 metre. For this part of the experiment there is no need to measure the gradient.

**The ball may not roll down the table in a straight line. Does this matter?**

You could answer this question experimentally or theoretically. The experiment approach would be to observe whether the ball does "wander" off a straight path down the slope—for instance because of a sideways tilt of the table, or because the table top is not flat. If it does wander off, does this affect the measured time it takes to cross the "finishing line" by an amount that is significant compared with the time and with errors in measuring that time? The theoretical approach might be to calculate the extra time it would take if it deviated by a given amount from the proper path. For example, if the ball deviates by as much as 0.3 m to either side of a straight line 1 m long, the error in the distance it rolls will be less than 10 per cent, and in the time, less than 5 per cent. How much is 5 per cent of 2 seconds? Can you measure this with your stopwatch? Do you get the same time from one measurement to the next, even if the ball rolls down more or less the same path each time?

We want you to time how long it takes the ball to cover the full distance. For timing the runs, you will want to use the stopwatch. You might try doing the timing with a sweep-hand of a wrist watch; you will see that (unless you are very skilled) this instrument is not sufficiently accurate for the job. But even using this modern equipment does not take all the fun out of the experiment. For you will need to train yourself to get an accurate timing at the beginning and end of the descent. In many modern versions of the experiment, there are devices for automatically starting and stopping the clock; these make it easier, for their inherent inaccuracy is far less than that of other parts of the experiment. But, with a manually operated timing device, you are at the limits of accuracy of your experiment, just as Galileo was. You can practise starting the watch just as you release the ball, and stopping it just as the ball strikes something at the terminus that, preferably, gives a noticeable sound. You should also give some thought to the best way of releasing the ball—having tried it a few times by holding and releasing it from your fingers you may consider this not good enough. (What if your fingers vary in their degree of 'stickiness' during the experiment?) Also you might consider wiping the table top with a duster before you start. Only when you have these various factors under control and repeated readings are giving reasonably reliable results should you start recording the measurement in earnest. Note that this is just what Galileo did. Having taken the average of the readings and recorded the distance, you should time the runs over a series of shorter distances. Record your readings in a notebook in the form of a table, as shown in the example. (Don't worry about the final column of the table—that will be added later.)

| Distance of run (cm) | Time of run (seconds) | | | | | | The square of the average time ($s^2$) |
|---|---|---|---|---|---|---|---|
| | Individual runs | | | | | Average time | |
| | 1st | 2nd | 3rd | 4th | 5th | | |
| 90 | 3.0 | 2.9 | 2.9 | 3.0 | 2.8 | 2.9 | 8.4 |
| 75 | 2.4 | 2.6 | 2.6 | 2.6 | 2.3 | 2.5 | 6.25 |
| 60 | 2.3 | 2.4 | 2.2 | 2.3 | 2.3 | 2.3 | 5.3 |
| 45 | 2.0 | 1.8 | 1.8 | 2.2 | 2.0 | 1.95 | 3.7 |

**Carry out the experiment as described.**

Having recorded your readings we want you now to pause and take stock of the situation.

Note first we have already given you a number of general tips—perform a preliminary experiment to finalize the design, take an average of repeated readings, record results in a notebook, show your readings in tabular form. We do not want to have to repeat these tips every time you come to do an experiment. We have therefore produced a special book entitled *The Handling of Experimental Data*, which contains, among other things, this general type of advice. We shall refer to this book as *HED*. If you

have had little previous experience of practical work you will probably find *HED* rather difficult to digest in one session—we shall therefore direct you to certain selected sections of it as and when the occasion arises.

Having collected your raw data, i.e. the distances and their corresponding times, we want you now to verify the result found by Galileo. This involves calculating the squares of the average times (i.e. filling in the final column to the table) and plotting a graph of distance against $(\text{time})^2$. If the distance is indeed proportional to the square of the time, this graph should yield a straight line passing through the origin.

**Now plot your graph and verify Galileo's distance-time relation, as quoted on p. 27.**

*HED:*
(i) In order to learn what this book contains and why we consider it important for you to do practical work, read the introduction.
(ii) If you had any difficulty in knowing how and why you should take the *average* of the set of timings, read *HED* 2.1.
(iii) Read *HED* 2.12 on the need to keep a notebook and 2.13 which gives hints on performing calculations.

Read *HED* 2.7, 2.8, 2.9, and 2.10 which explain proportional relations, and why graphs are considered important, and gives hints on how to plot them and extract information from them. (In *HED* 2.9 reference is made to the calculation of the error on the slope of a graph. You need not worry now about this point as this requires a knowledge of earlier sections.)

### 1.4.4 Introduction to the second part of Galileo's experiment

By this point you know that you should have obtained sets of readings which fit the relation: distance proportional to the square of the time. But this applies for a ball ROLLING down an incline; *how can we know that it also applies to the same ball falling freely*? Timing how long it takes the ball to drop freely through various fractions of a metre would be tricky—the time intervals would be uncomfortably short. Galileo recognized the difficulties of performing such a direct experiment. So he thought of approaching the problem indirectly by using his inclined plane. He repeated the experiment using steeper inclines (as he says in his description). He found that the relation held at any inclination (*if you wish* you can repeat the first experiment at different inclines to satisfy yourself that this is so). He then argued that the relation would hold in particular for the limiting case of a vertical incline. By measuring the distance the ball rolls in a given time down planes of various inclinations, he hoped to extrapolate to get a distance rolled down a vertical plane. This he was to equate to the distance a ball would travel in free fall in the given time. The question was—how to extrapolate to a limiting case? Look at Figure 6.

AB is a vertical diameter of a circle, CB is a chord, and C′B is another chord, longer and steeper than CB.

Galileo guessed that the time a body would take to roll from C to B would be the same as the time from C′ to B. If this hunch (and it was nothing more) could be verified experimentally for several different chords of the circle, like CB, C′B, C″B, etc., it would seem reasonable to suppose it might hold good all the way up to the vertical chord AB. This is called the 'circle-chord theorem'. Galileo argued that if the distance-time relation is found to hold for different lengths *and* different slopes, even very steep, 'almost vertical' slopes, then it must hold also for the vertical. In this way he solved the problem of extrapolating from the measurable case of descent along a relatively shallow incline to the non-measurable case of free fall.

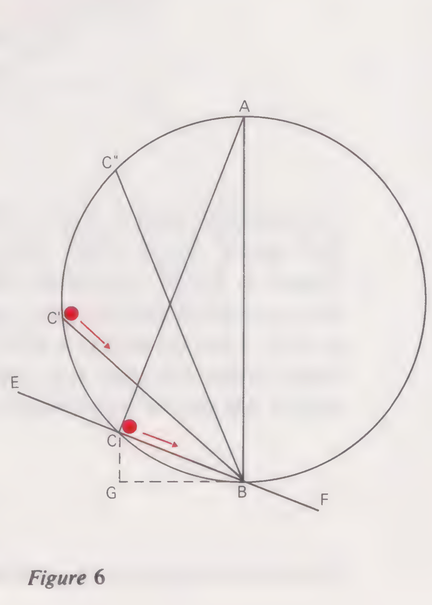



*Figure 6*

You may be wondering how Galileo got his hunch. The history is obscure, but it seems that his experiments in mechanics started, not with the inclined plane, but with the *pendulum*. Very early in his scientific career he did experiments with the pendulum. He found the time for completing a back-and-forth swing to be independent of the amplitude of the swing, i.e. how far it swings. If you take the pendulum bob as a point falling and rising along a circular track, then the time of descent along all *arcs* of a circle to the lowest point are the same provided the arcs are small. Roughly speaking, the longer the arc, the more steeply inclined it is at the extremity, the more quickly the body starts its descent, and so makes up for the extra distance to be travelled to the bottom. The circle-chord theorem probably occurred to Galileo by analogy, when he had shifted

his attention to the problem of free fall, and used the straight incline for experiment. As it happens, while the circle-chord theorem is true, the circle-arc theorem is only approximately true for small arcs.

The next experiment we want you to do is to *verify the 'circle-chord theorem'*, i.e. for a number of inclines measure the distances travelled in a fixed time of one second and check that they correspond to chords of a circle (like CB, C′B, C″B). From the calculated diameter of this circle you can then extrapolate to the vertical case, i.e. calculate the length of the chord AB which, as Galileo assumed, should be the distance the ball will travel in free fall in one second. Thus, on Galileo's reasoning, *you will have arrived at a measure of the acceleration due to gravity.*

### 1.4.5 The second experiment: what you have to do

Measure the time for the ball to roll down various lengths of track, keeping the slope of the table fixed. By trial and error find the distance that corresponds to a one second time of descent. This distance is CB in Figure 6.

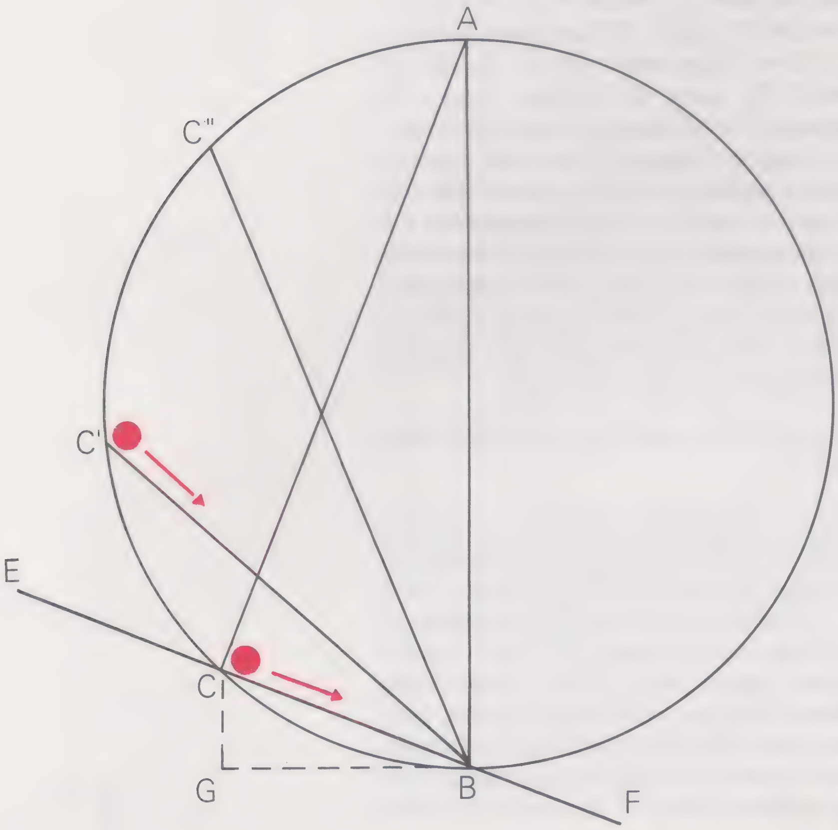



*Figure 6*

The question then is how to calculate the distance AB, i.e. the distance a ball would travel when rolling down a vertical slope. Look again at Figure 6. ECBF represents the table top. We have drawn a horizontal line through B and dropped a perpendicular to it from C; the intersection is at G. The two triangles BCG and ABC are similar. (If you do not know what *similar* triangles are, look at *MAFS*, section 2.E.) Consequently the length AB can be found from the relation

$$\frac{AB}{CB} = \frac{CB}{CG} \qquad (1)$$

(Corresponding sides of similar triangles have the same ratio.)

We already know CB. It is the length for a one second descent down this particular slope. If we can somehow measure CG then we have AB.

**Can you think of a way of measuring the ratio CB/CG without using a spirit level and a plumb line?**

One way of doing it is suggested by Figure 7. Here we have drawn in the table, legs and all.

Then, provided the table top is flat and its legs are of equal length, the triangles CGB and HKJ are similar so,

$$\frac{CB}{CG} = \frac{HJ}{HK}$$

You can measure HJ and HK directly (you will see that you do not really need a plumb line for this, for the error caused by slight deviations from the vertical is small). So now you have

$$AB = CB \times \frac{HJ}{HK} \quad \text{.......................................}(2)$$

and everything on the righthand side of the equation has been measured. You can now estimate the diameter of the 'circle of one second fall time'.

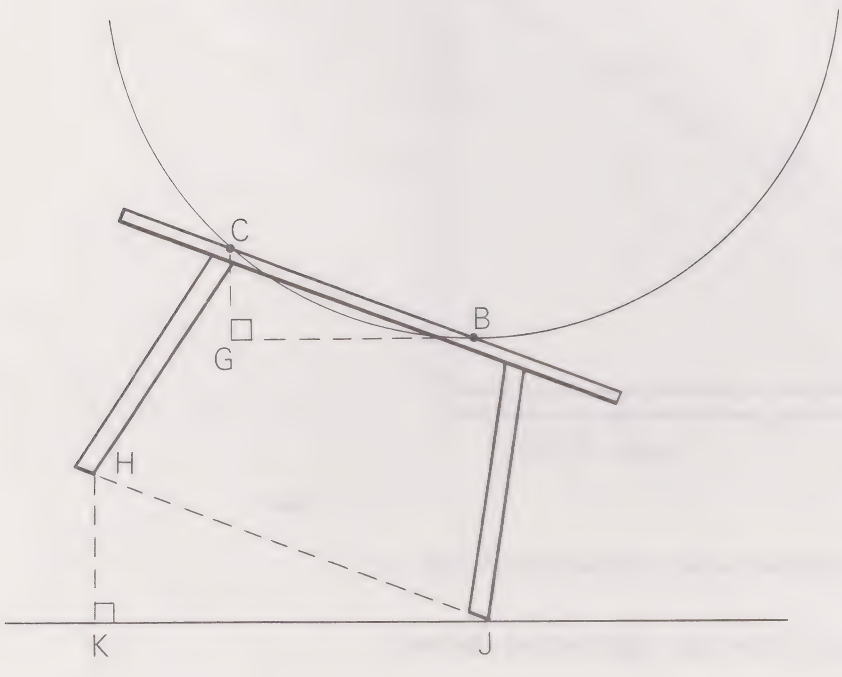



*Figure 7*

Next, change the tilt of the table and find the value of CB for the new inclination, i.e. the new distance travelled in one second (the distance C′B in Figure 6). Also measure the corresponding value of HK. If the 'circle-chord theorem' is correct then the value of AB obtained from equation 2 with these values of CB and HK should agree with the value obtained with the first inclination of the table, i.e. CB and C′B should be chords of the same circle.

Repeat the experiment for a total of at least five different inclinations.

**Substituting the readings in equation (2) is certainly one way of verifying the 'circle-chord theorem'. In *HED* 2.8 you were advised to display results in the form of a graph whenever possible. How could you do so with your present results?**

In order to see how you can display your results graphically we rearrange equation (2) so:

$$\frac{AB}{HJ} \times HK = CB \qquad (3)$$

Here we see that the two quantities we are varying, CB and HK, are proportional to each other. Therefore a plot of CB against HK should yield a straight line passing through the origin—if the 'circle-chord theorem' is valid, i.e. if AB is a constant. (Here we are assuming that the table is sufficiently rigid so that HJ does not change very much as the angle is altered.)

**Plot the graph.**

**How can you estimate AB from it?**

The slope of the graph, i.e. $y/x$ in Figure 8 gives the value AB/HJ. Having measured the length HJ you can calculate AB.

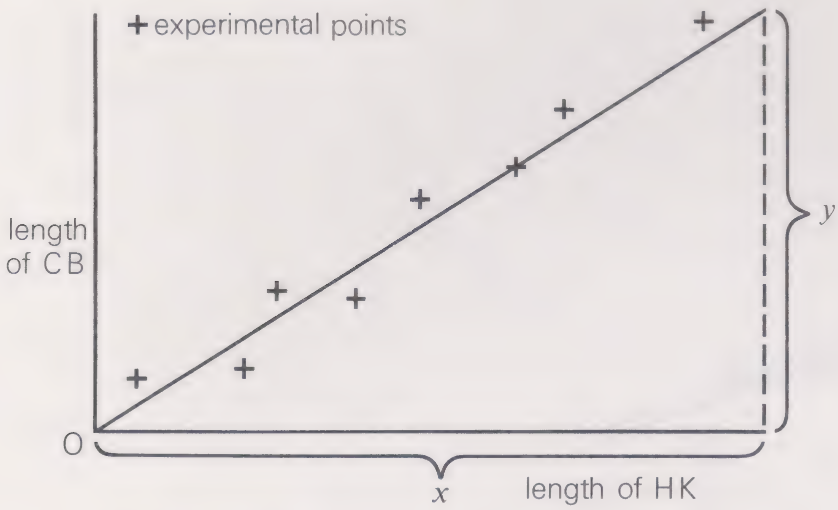



*Figure* 8

So you have found the height AB down which the ball should 'roll' in 1 second.

The obvious thing to do is to drop it from that height and see whether it takes 1 second.
We suggest you do this right away.

### 1.4.6 A quick test of the extrapolation from inclined plane to free fall

You may need to do the test out of doors if your ceiling isn't high enough!

Hold the ball at the height AB above the floor or ground (you may need to stand on a stepladder or use a convenient window or the stairs). Drop the ball, starting the stopwatch simultaneously, and stop the watch when you hear the ball hit the floor. Repeat this measurement 10 or more times and calculate the average time.

Do not read on until you have done this experiment and answered these questions:

**Did you get a time of 1 second? Did you expect to?**

You should, in theory, have measured a free fall time of about 0.8 seconds.

The difference, 0.2 seconds, is about the same as the probable error in your measurements.

You would need a more precise timing system to check the validity of this hypothesis.

Perhaps now you will appreciate Galileo's dilemma. His timing system was, if anything, inferior to yours. He could measure *relative* times quite accurately with his water clock, but to measure absolute times, times in seconds, he had to compare some sort of continuously repeating process with the length of the day or with some other astronomical measure of time. The best available device of this kind was the pendulum, but the 'pendulum clocks' of Galileo's time were exceedingly primitive and inaccurate; indeed it was not until 1657, fifteen years after the death of Galileo, that the Dutch scientist Huygens invented an effective pendulum clock.

Galileo was well aware of the importance of defining physical constants and measuring them; yet for this most important one, the height of one-second free fall, his estimates are given casually, and are not consistent. In some places, they seem to indicate a value a bit higher than the correct one; in others, they indicate the value obtained by extrapolation from the inclined-plane; but he never committed himself in this case as he did in others. It is most likely that he was simply *unable* to determine the quantity consistently. Yet it was critical if his theory was to hold!

Galileo was confronted with the problem of trying to measure something right at the limits of precision of the instruments at his disposal. But, in addition, his experiment was being affected by a phenomenon that was quite unknown to him or to anyone else at the time—that of rotational kinetic energy.

Perhaps you *did* find a difference between the average of your measured times of free fall and the time of 1 second 'predicted' from the previous experiment.

But was it a *significant* difference? That is, did it differ from 1 second by more than the probable error in your measurements?

After all, you are using a stopwatch which has divisions of a fifth of a second. You could have drawn various straight lines to fit equally well the set of points you plotted in the graph of CB against HK.

All in all, your probable error may well have been as great as $\pm 0.2$ seconds. Can you say, definitely, whether or not your experiment confirms the validity of extrapolating from rolling down an inclined plane to free fall?

Probably you cannot. If you care to look up Appendix 2 (Black) you will see that the effect of *rotation* on a rolling ball is to use up some of the energy that would otherwise be available to give it linear kinetic energy down the inclined plane. The result is that it will take about 20 per cent longer to *roll* a given distance than to *slide* the same distance on a frictionless surface. As a result, the time the ball should take to *fall* the height AB should be about 20 per cent less than the time you would predict by the extrapolation you did.

The importance of making due allowance for the energy going into rotation can be demonstrated in a very marked fashion by considering a pair of

**Summary of the Galileo Experiments**

*Apparatus required*

A table (more than 1 metre long)
Stopwatch
Ball
Ruler or tape-measure

**Experiment 1**

Tilt the table so the ball takes 2 to 4 seconds to roll 1 metre.
Time the run over about half-a-dozen distances taking at least five readings for each distance.
Average the time for each run and square it.
Plot distance against (time).[2] Verify that it is a straight line passing through the origin.

**Experiment 2**

Vary the slope of the table, and for each slope measure the distance covered by the ball in one second, and the distance HK of the inside of the raised table leg above the level of the floor (Fig. 7, p. 31).
Plot a graph of the distance the ball rolls in one second against HK. Estimate the slope of the straight line obtained. Measure the distance HJ between the feet of the legs of the table, and hence determine the height of AB (Fig. 6, p. 30) through which the ball would roll down a vertical plane in one second.

**Test of the Experiment**

From a height equal to this estimated value of AB drop the ball several times and see whether it does indeed take one second to strike the floor.

**Final Report**

This should be written for submission to your tutor.

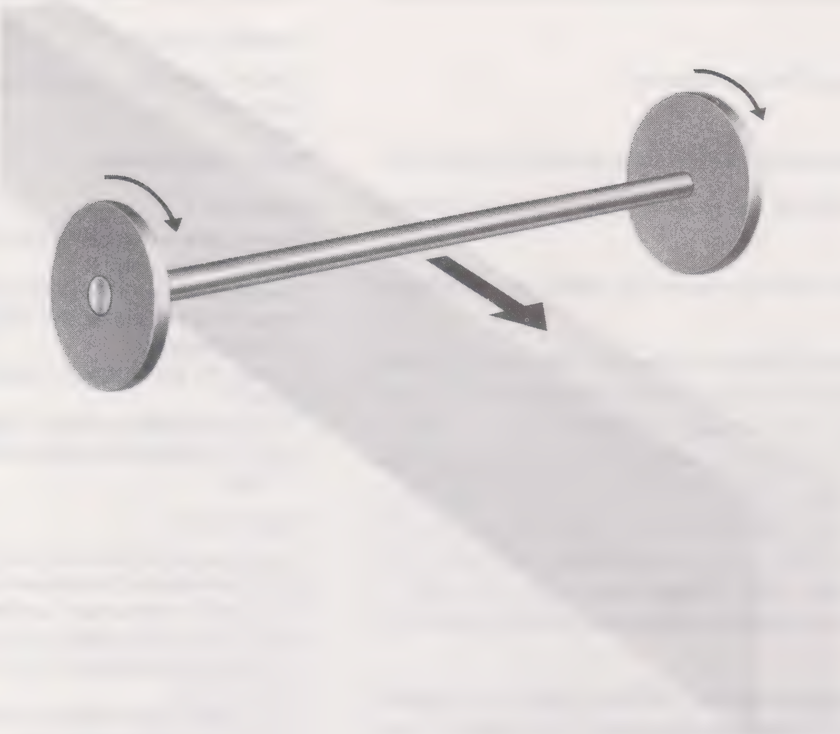


*Figure* 9

heavy wheels on an axle, rolling down an incline on its *axle* as in Figure 9.

As you can probably well imagine it would take much longer for this object to *roll* to the bottom than to *slide* the same distance.

Another way of seeing what happens is to look at Figure 10, where a ball is shown rolling down an almost vertical incline.

In the case shown, the almost vertical frictional force is necessary in order to impart rotation to the ball—but the same force also partly cancels out the gravitational force; in so doing it reduces the rate of descent compared to the case where the ball falls freely with no increase in its rate of rotation.

If you have done the inclined-plane experiments at school, you may have noticed that the weight is usually carried in a little cart, with light wheels to avoid this problem, and in advanced mechanics, the kinetic energy of rotation of the wheels is taken into account when the calculation is made. In this way, the modern student is led past the pitfalls that Galileo encountered. But how much more interesting it is if, at least once, we can see the mixture of truth and error which this great scientist showed in creating the modern science of mechanics.

Incidentally you should note that the fact the ball rolls rather than falls does not invalidate either the distance-time relation or the 'circle-chord theorem'; this is because the rate of rotation increases in the same way as the rate of fall down the plane. The error only comes in when the extrapolation is made from the case of rolling down a vertical plane to that of falling freely.

**If you already have some background knowledge of physics, particularly the idea of moments of inertia, you might like to consult Appendix 2 (Black) which goes into these points more fully.**

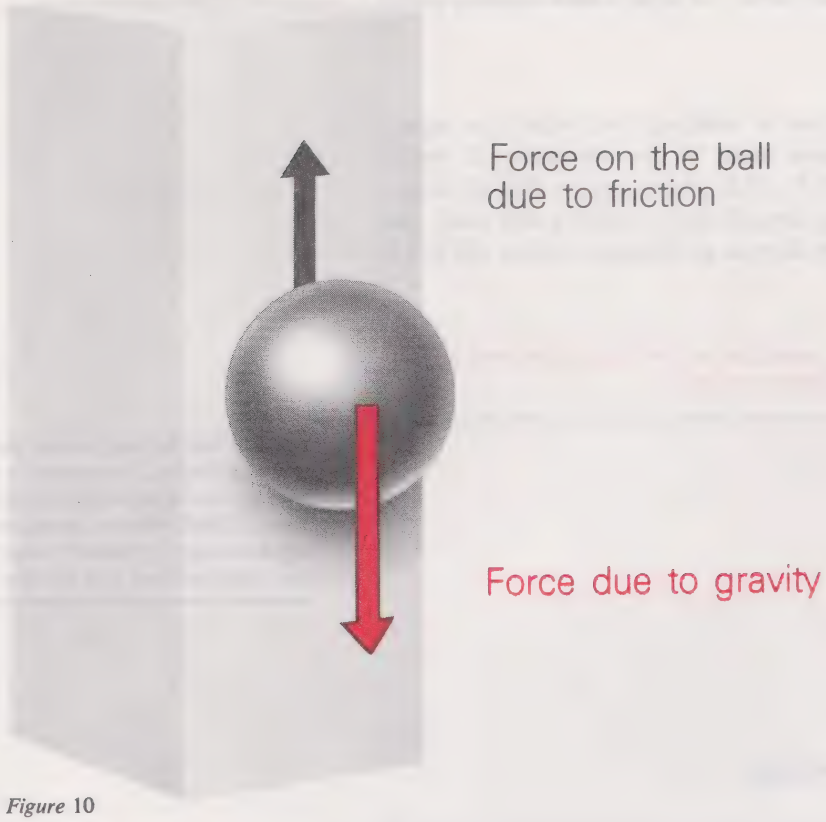



*Figure* 10

### 1.4.7 Some remarks about errors

Now that you have done an experiment, we want to draw your attention to the question of errors and limitations on the accuracy of experimental data.

You will have noticed that in repeatedly timing the ball rolling down a given distance at a given inclination, you did not always get the same value of the time.

**What reasons can you give for this?**

There are several possible reasons. No matter how smooth the surfaces of the ball and the inclined plane, there are always slight imperfections, specks of dust, etc. These will affect successive runs in slightly different ways. Though you may have thought of a very clever way of releasing the ball, it will not always have been released in *exactly* the same way. You will start and stop your watch in slightly different ways each time. These effects all give rise to random errors—sometimes they lead to an overestimate and sometimes to an underestimate of the time interval.

In addition there can be instrumental errors—your table top may not be perfectly flat, the watch may not respond immediately you depress the knob. There can also be 'personal errors'—you may have a systematic tendency to start the watch too early or too late compared with someone else doing this experiment (this is over and above the random fluctuations in timing). There are errors of bad technique—you probably notice that the reading on the watch differed depending on the angle at which you held the instrument—did you always hold the dial at the correct angle to take a reading? And how about extraneous influences like air resistance and draughts—in really accurate work these would have to be excluded.

These are some of the ways in which the data of this particular experiment could have been faulty.

**We should now like you to read Section 1 of *HED* in which is given a general discussion of errors.**

Read *HED* 2.14 which describes how to write up final reports on experiments. (You will find here reference made to the calculation of errors. This subject is dealt with in *HED* 2.2 to 2.6. This is quite a difficult subject and you need not work your way through these sections this week. But some time soon you must find the time to go through at least *HED* 2.2, 2.3, 2.4 and 2.6.)

**Now write up in final form for submission to your tutor all the work you have done in connection with the Galileo experiment.**

You will find full instructions about how to submit an assignment to your tutor in the Tutor-marked Assignment Sheet, S10001, which is among the supplementary ('loose-leaf') materials you have been sent with this text.

**Section 5**

## 1.5 The nature of scientific knowledge

Having seen something of how an experiment is made, its pitfalls, and the sort of conclusions that you can draw from it, let us now look at the *nature* of scientific conclusions. What do we mean by a 'scientific' statement, compared with one in everyday language? Look first at these two statements concerning the phenomenon of falling bodies you have just been experimenting upon:

(A) Judging from their impact on landing, objects falling from a greater height fall for a longer time and arrive with a greater speed.

(B) For a body in unresisted fall, under constant acceleration $g$, $v = gt$, where $v$ is the instantaneous velocity at time $t$ after the instant of release from rest (do not worry about the definitions of these terms yet—they are defined in Unit 3).

**What are the relations between these two sorts of statement?**

Statement A derives from common experience and assumptions; it can be explained to someone without special training and can be shown by a simple experiment. Statement B contains several technical and mathematical terms whose meanings are not immediately obvious. It is precise, and its confirmation by experiment requires specialized equipment.

**(a) List the terms in statement B not used in everyday language.**

**(b) In what ways does B tell a scientist more than A does? In what ways less?**

**(c) If you are trying to explain A to someone with no formal training in science, will it help to invoke B?**

**(d) How likely is it that B was derived purely by careful observation of the phenomenon described in A?**

This example indicates that while much scientific knowledge has 'grown out of' everyday experience, the relations between the two are not simple and direct. Scientific statements have *precision* and *objectivity*; they use

(a) Unfamiliar terms: "unresisted", "acceleration", "instantaneous", "velocity".

a *specialized abstract language*; and they are the result of a close, disciplined analysis of experience. The relations between science on the one hand, and craft techniques and common experience on the other, have been changing over the centuries. Up to recent times, most of the problems of science were set up by the tasks of explaining naturally-occurring phenomena, both the regular (thus, 'how do we get a true picture of the external world in our minds?', 'what causes the tides?', 'why are some things heavy and some light?') and the irregular (such as eclipses, storms, rainbows). Explanations of the latter sort sometimes had political implications, for the answers replaced and excluded magic and miracles. Similarly, scientists obtained their experience of nature either by direct observation, or by borrowing results and techniques of experiment from craftsmen. Galileo was one of the first to develop or invent his own instruments for experiment (telescope, timing pendulum), and even these were closely related to applications, often ones he developed himself. But by the nineteenth century, experimental science developed a world of artificial experience, studying things and events which were first created in the course of research, in the artificially pure and stable conditions of the laboratory. For example, a number of pure chemical substances were isolated for the first time during the eighteenth century; and an even more striking illustration of this entirely new world of nature was the understanding and subsequent application of current electricity and electromagnetism, in the early nineteenth century. Although what we now call static electricity and ferromagnetism had been known and studied since antiquity, current electricity and electromagnetism (which do occur naturally) had been undetected and unknown until they were first produced under controlled conditions in the laboratory.

On the basis of its command of this new world of artificial nature, science could begin to penetrate industry on a large scale. The first application of current electricity and electromagnetism was in the telegraph, which suddenly enormously multiplied the speed of communication. Later in the century arose a totally new industry, providing a new source of usable energy—electricity. In the present century, all new industries depend on the application of scientific results; and even older craft industries (e.g. agriculture, textiles) are increasingly penetrated by scientific knowledge and a 'scientific' approach. Indeed, much of our present world of ordinary experience is now largely a product of science-based technology.

(b) B gives us a precise relationship rather than a general statement. It also makes the statement apply to any time, not just the moment of impact. But it mentions only time of fall, and not distance. Also it is limited to the case of "unresisted" fall.

(c) B would not be much use as an "explanation" of A since an understanding of B requires special knowledge of its technical terms.

(d) B could just possibly have been derived by observation; but to measure "instantaneous velocity" requires special equipment, and so B would require an *experiment* rather than merely looking at a falling body and commenting on what you observed.

## 1.6 The creative work of science

Most of the scientific facts used by scientists today, including those you will be learning in this course, have no obvious connection with craft practice or with ordinary experience. Indeed, as they are presented by teachers, it is often very hard to see where they came from, and by what processes. We will explain how the development of scientific knowledge separates it from its origins in creative enquiry; but first we consider the act of scientific creation itself.

The beginning of a scientific enquiry is a guess, a hunch, an idea of the way things might be. Unless the scientist is very unlucky, it will have some kernel of truth in it; but unless he is superhuman, it will also include errors. For example, an important error made by Galileo was in refining the common experience of falling things (statement A, p. 36) into the *law*† that freely falling bodies increase their speed in proportion to the *distance* fallen. This was an apparently simple scientific law, and only after years of work did he discover its falsity and obtain his equivalent of statement B, p. 36.

To describe the process by which the initial insight of a scientist is refined and corrected into a genuine result, we will use the idea of a 'problem' and to make this more precise, we will consider a set of examples of 'problems' (you are not expected to solve these here and now!):

(1) Given that $v=gt$ (as defined in statement B), calculate $v$ if $g= 9.8\ \mathrm{m\ s^{-2}}$ and $t = 10\ \mathrm{s}$ ($\mathrm{m\ s^{-2}}$ means metres per second per second.)

(2) Measure *instantaneous velocity* using a camera to take pictures every hundredth of a second to confirm by experiment that $v=gt$. *Velocity* is defined as the distance travelled in a given time in a given direction. In the present case, however, where the velocity of the body is continually changing, the distance travelled in a given time will only be a measure of the *average* velocity during that time interval. *Instantaneous velocity* is the velocity at a given instant and strictly speaking could be measured only if the time interval were vanishingly small.

(3) Assuming that air resistance is proportional to $v$, obtain a relation between $v$ and $t$, for a body under constant acceleration (i.e. removing the requirement that the motion be unresisted).

(3a) Same as 3, but assuming air resistance to be proportional to the square of the instantaneous velocity, $v^2$.

(4) Decide by experiment whether the air resistance to a moving body is proportional to $v$, to $v^2$, or to some other power of $v$.

(5) Decide whether the air resistance to moving bodies is fundamentally different at high speeds and at low speeds?

What is involved in solving each of these problems? Problems 1 and 2 are straightforward exercises, one of calculation, the other of experiment. Problem 3 is a purely mathematical exercise. It could be put in the form of a 'differential equation' and then solved. Problem 3a looks similar but is not; for in this case the equations cannot be solved analytically, although approximate solutions are possible. Problem 4 is even more open-ended; the design of an experiment which would yield the appropriate data is a sophisticated exercise, and then one would need to 'fit a curve' to the data to estimate the correct 'index', if any one could be found. Problem 5 poses a very general question and requires a background in theory† and experiment (for example of the theory of 'turbulence' and 'turbulent flow') before it can be investigated in any detail.

Problems 1, 2 and 3 can be described as 'exercises'; by known techniques, one can achieve the known answer. When such problems are given to a student, their function is not to enable him to 'rediscover' known results, but to train him in the elementary skills of scientific work or to test his comprehension of the concepts involved. The other problems in the list are genuine scientific problems; there is no straightforward method using standard techniques whereby a reliable answer can be obtained. To the extent that any problem presented to the scientist is not a routine exercise, 'framing the problem', that is, asking the question appropriate to the problem and to the tools and apparatus that can be brought into use in answering it, is creative work. The process necessarily starts with a guess, a hunch, an insight or a speculation, sufficiently precise to indicate the path of development, but sufficiently vague to allow the idea of the nature of the problem to grow during the work.

### 1.6.1 Limitations on research

What determines the sort of hunch a scientist has, the sort of questions he asks of his material? Four factors, at least, are involved. One is his own capacity to design a crucial experiment, to think through the nature of the problem; his 'genius', if you like. A second is the equipment and apparatus he has at his disposal; their limitations determine the shape of the questions he can ask and hope to get answers. A good example of this is provided by the Galileo experiment you have just done. Other examples of these limitations in modern science will show up in later units, for instance, the limit of magnification of the optical and electron microscopes discussed in Units 2 and 14. A third is the prevailing spirit of the ideas of his fellow scientists. It is hard to think 'out of the rut' of the conventional wisdom of accepted ideas. Scientists who do so may even be unpopular with their colleagues, or their work not accepted for many years. But perhaps the most important overall factor is the dominant shape of the thought of the society in which the work is done, which is itself determined by the structure of that society. Thus in England of the nineteenth-century Industrial Revolution and of unrestrained industrial development, there was a tendency amongst the scientists to a very mechanistic view of the world. Mechanical models for force, heat and energy prevailed amongst the physicists, whilst terms such as the 'struggle for existence' and 'survival of the fittest' were in use amongst the biologists. By contrast, for example, the biological models of the late twentieth century make much more frequent use of terms such as 'community', 'interaction', 'feedback' and 'regulation', concepts more akin to today's prevailing ideology within Western society.

How a scientist gets the idea which produces the problem is a very complex question to which no very precise answers can, in fact, be given; no 'scientific method' will generate original problems. It also requires judgement to know whether a problem can be successfully investigated at a given point in the development of a science. Galileo himself was aware of problem 5 (p. 38), but he sensibly chose to ignore it in favour of problems that he could solve—those neglecting the effects of air resistance. Investigating significant new problems is hazardous work, for the chances of failure are high; the less that the paths to a solution are charted, the greater the pitfalls that lie in the way. As you study science, you will learn the names of great scientists who are credited with the discovery of basic facts and laws. These facts frequently seem so simple and obvious that it is hard to imagine why it took a great man to discover them. But this appearance may be deceptive; often the more simple and elementary the fact now appears, the more deep and difficult the work was which led to its first discovery.

## 1.7 Establishing scientific results

Conceiving an original scientific problem is an act of creation requiring the free play of the imagination; but once the scientist is involved in working on that problem, his inspiration must be supplemented by perspiration.

Without careful, systematic, self-critical work, his initial insight will remain half-baked. Thus, had Galileo contented himself with the plausible law that speed increases in proportion to distance, for which he could even provide a (fallacious) derivation from the law that distance is proportional to time-squared, he would never have achieved his successes in mechanics. This hard work is necessary because there is no standard method whereby any scientific problem can be solved, as on a computer. This is because no new scientific result can be 'proved' in the way that a student's routine exercise can be definitely solved, with one right answer out of the many wrong ones. A scientific result is achieved by the combination of reason and experience, and their union can never be simple or perfect. Scientific statements deal with abstract concepts. They are not expressed in the ordinary language of everyday use.

**Do you recall an example of an abstract concept from within this Unit?**

Yes, the concept of 'instantaneous velocity', statement B, p. 36.

Of course, the concepts used in science must in the last resort be related back to ordinary experience, so that scientists, who are only human, can reason with them (just as it has been observed that the strangest science-fiction monsters are composed of very ordinary parts). But a close relation to ordinary experience may actually be misleading. We speak freely of 'hot and cold', 'fast and slow', 'heavy and light', as opposed qualities, but if, for example, in describing the motion of bodies, we were to be restricted to words like 'fast and slow' we would find it impossible to master the science of mechanics. Indeed, this idea of 'opposing qualities' persisted until the time of Galileo, and caused trouble to him as well as to his contemporaries.

Quite soon in this course, you will encounter some concepts whose relation to ordinary experience is very indirect, and which can be studied only in the artificial conditions of the laboratory. (Recall the remarks on p. 37 about the development of a world of artificial experience by modern science). For example, the study in Unit 2 of the differing scales of length involves using 'electromagnetic radiation' of various wavelengths: radio waves, light, ultraviolet and X-rays. We can unify and explain these phenomena in terms of a theory of *electromagnetic radiation*, itself an effect of electric charge in accelerated motion. But what is 'electric charge'? We can *show* you some of the simpler effects of electric charge by asking you to do the experiment of rubbing a comb and seeing that it attracts bits of paper. But you still can't see or feel the charge itself, although you can see a spark or feel a shock. Thus we are really no further forward in answering the question: what it *is*? Scientific research does not attempt to answer such a question in a simple and direct way; rather, by building up knowledge of its properties, it approaches (but never reaches!) a 'true' understanding of its nature.

You will also see that scientific knowledge about any one concept is composed of statements about it in connection with *other* concepts. It might

seem that the whole process of definition and explanation goes around in a circle! In most practical cases, it does not. At any given point in the development of science, some concepts are better understood and more firmly related to experience; and these will be used as the foundation for those newly invented. However, in teaching the foundations of a subject, we find ourselves with an embarrassing freedom of choice; and we will not try to conceal this from you. For instance, as you will see in Unit 4, classical dynamics depends on 'mass' and 'force'. The definition of these has given trouble ever since Newton's first attempt in his classic book *Principia* (1687). One can only measure mass through some effect *involving* forces such as collision, or gravitational attraction. But then if one considers force as a cause of motion, one can measure it only in terms of the velocity it imparts to a given mass! At this point, philosophers of science can assist the advancement of scientific knowledge; for they analyse the concepts that scientists develop and use in a practical way, and examine how they might be clearly defined and consistently related among themselves.

### 1.7.1 The design of experiments

It would be comforting to think that all these difficulties with concepts are relatively unimportant, since science depends basically on 'facts' which are results derived from experiment or observation of the natural world. But here too the work of science requires skill and judgment, and is open to error. For whatever the source of the data the scientist uses, it is inevitably imprecise (see *HED*, section 1) and can only approximate to answering the questions which the scientist is really asking. Also the experiment itself must be designed for the testing of those effects that can be studied with the available tools. These will usually be very special ones (as the 'circle-chord theorem' in the Galileo experiment) which are not found in direct observation of nature. To the extent that the conditions of the experiment are different from those 'outside', there will be difficulties and pitfalls in applying the conclusions of the experimental research to natural phenomena themselves. You have already seen one such classic pitfall, in the very simple case of the rolling of bodies down an inclined plane; imagine how much more difficult is the job of extrapolating from an experimental situation in a complex physical science, to say nothing of the biological, or earth sciences. We can illustrate the inherent difficulties and limitations of experiment, by considering problem 2, p. 38: measuring instantaneous velocity by a stroboscopic camera (one that takes pictures by light-flash every given fraction of a second).

**Why have pictures every hundredth of a second? Why not have a simpler apparatus, and take them every tenth of a second? Or should we rather do the job properly, and have pictures taken every nanosecond ($10^{-9}$s)? (N.B. You will learn how such short time intervals can be measured in Unit 2.)**

The answer is that for some purposes, a tenth of a second is not quite good enough, a hundredth of a second is adequate, whereas a nanosecond gives too much detail. The time-intervals must be small enough so that the *average velocity* between them is a good approximation to measuring the *instantaneous velocity* at any point of time in the interval. Also, there must be enough estimates of this average velocity for a test of any hypothesis about the behaviour of the falling body. If the body falls only 1 metre, the total time of fall is less than half a second, so tenth-second photographs would give only three average velocities, but a fall of 5 metres would give about a second for the fall, and enable ten estimates of average velocities. On the other hand, if one is concerned to see the effects of air resistance, turbulence, etc. at very low velocities, then one might want a very closely

spaced sequence of photographs, for which even hundredth-second intervals might be insufficient.

**Does this experiment measure 'instantaneous velocity'?**

Of course not! Even a nanosecond interval would not do that. But if the thing can't be measured then what is it?

Even when we take a series of photographs as described above, they will be slightly blurred; there will be a distortion near the edge of the frame, and there will be systematic and random errors in the timing of the photographs. For the purposes of the sort of measurements that we are trying to make here these effects don't matter; but this is because the progress of science, made possible in this case by Galileo's work, results in the technological development of tools such as clocks and cameras, which render a repetition today of his original experiment apparently easy and trivial. However, the powerful and complex tools used in contemporary science, such as the high-energy accelerators of elementary particle physics, are designed for experiments done at the very limit of their own capabilities. There we find the same difficulties in the production and interpretation of experimental data that Galileo had with his primitive equipment.

Highly accurate experiments with bodies falling through the air at different speeds, would not 'confirm' the relation $v = gt$; they would show that it is false. The experimental data will fit the predicted curve, only when speeds are not too great and measurements not too precise. This deviation of experiment from theory is due to air resistance (and also partly to the inevitable experimental error that remains even in 'highly accurate' experiments). But study of the effects of air resistance presents problems of very great difficulty. Most of the mathematical equations derived from the physical data cannot be solved in any neat way; the measurement of air resistance is itself a difficult procedure; and the interpretation of experimental data is complex.

### 1.7.2 Models

A student doing a 'set' experimental exercise can obtain his data and derive a result that he knows agrees with that quoted in a text book. But we have seen that for the scientist who is handling imprecise data in the hope of getting evidence for a conclusion about artificial concepts, life cannot be so simple. For the scientist cannot 'prove' a new result in his research; at most he can establish it by an argument that is 'probable' and 'reliable'. But the patterns of argument in science are not those of ordinary persuasive or plausible reasoning, like those of the politician or advertiser, for instance. They depend not only on the marshalling of experimental observations, but on the analysis of those observations according to a set of logical procedures that are universally acceptable to scientists working in that particular field. The type of procedure used differs somewhat from one scientific field to another, depending, for instance, on whether it is predominantly an experimental field (like today's biochemistry, for example) or a theoretical one, where experimental data is scarce but theoretical ideas are plentiful, like cosmology, at least until recent years. In the former case the argument might proceed by the presentation of a new experimental result which fits, or fails to fit, a formerly accepted theory. In the latter, much of the scientist's work may go into the making of a *model*†: a conceptual or mathematical structure whose properties can be systematically explored, in the hope that some of these will agree with experiment, and so provide clues to the causes of

the phenomena. The relation between the model and the real things and processes is one of *analogy*: a similarity between important features on both sides.

**Can you think of some examples of such models or analogies?**

**Some you will meet later in the course include billiard balls for models of molecules of a gas (Unit 5); waves in water as a model for sound or light waves (Unit 2); a sheet of rubber deformed by a stick as a model of a field of force (Unit 2); a pump as a model for the heart (Unit 18). You will find more examples in succeeding course units.**

In a sense all scientific theories are models, based on analogy; the mathematical point whose motion is described by the relation $v = gt$ is a *model* for the *real* falling body. But in cases such as this, the similarities are so strong that for many purposes we can consider the equation as *really* describing the behaviour of the falling body itself. When the scientist operates in this way he hopes to have something stronger than a model. For, if his conclusions *explain* the phenomena in some sense, he can consider himself as having achieved a *theory*. You will soon see an example of such a 'theory', in the explanation of light as consisting of electromagnetic radiation (Unit 2); another is Newton's theory of universal gravitation (Unit 4).

### 1.7.3 Hypotheses

On the other hand, when the work on a problem involves some interaction with the real world, through experiment or observation, the role of *hypotheses*† becomes crucial. An hypothesis is a statement about the things being studied, put forward not as a conclusion to be accepted and developed, but only as a tentative conjecture, serving as a guide to investigation, rather like the 'hypotheses' that we suggested were made by rats as to which doors had food behind them. Observation and experiment must be done in a systematic and disciplined way; good scientists do not simply 'go out and collect' data. Although chance discoveries may start off a problem, the data which is eventually used must be produced methodically, so that it is as free as possible from human error in its compiling, and also protected against errors of interpretation. A common way of tackling a problem is to design the experiment so that it *tests an hypothesis*. In doing this, the scientist must state exactly what the experiment is about; he must organize the production and recording of data into a particular routine; he can be clear about the sorts of data that confirm or refute the hypothesis (or leave it undecided); and he can more easily locate errors in the interpretation of the data.

The way in which an experiment is designed to test an hypothesis must be carefully planned if correct conclusions are to be drawn. This is especially true when the data cannot be interpreted at a glance, either as they stand, or when plotted on a graph. For example, when the scientist wants to know whether two effects are independent of each other, or are related so that when one occurs the other also tends to, then it is necessary to analyse the results mathematically and statistically. These statistical techniques are very powerful, so much so that quite unrelated sets of data can, with desire and ingenuity, be shown to be 'correlated'. Examples of such false or misleading correlations come most frequently from the medical sciences, although they are certainly not unknown elsewhere. One of the most striking in recent years was produced in a study of the rapid increase in the occurrence of deaths due to the disease of coronary thrombosis, when it was shown that the only factor examined whose increase in the community paralleled that of the disease was the issue of television licences. It could be argued to 'follow' from this that ownership of a television set—or a licence for one at any rate—was a factor in causing the deaths by coronary thrombosis. However, no one would regard such a correlation as being of much use in helping find an explanation or a cure for coronary thrombosis!

To guard against such pitfalls, the founders of modern statistical methods devised principles and rules for such work; foremost among these is that every experiment be designed to test a particular hypothesis. From the results of the experiments a statement of statistical probability can be made, the probability that the hypothesis in question is true. The scientist must then use his judgement, aided by the experience of his field, to decide whether a particular level of probability or truth (or falsity) is good enough. For some purposes, 95 per cent (odds of 20 to 1) is good enough; but for others he cannot be satisfied with less than 99 per cent (100 to 1). If you are not clear about such aspects of probability, look at the examples given in Appendix 1 (Red) (p. 49).

### 1.7.4 Deductive and inductive inference

Scientific problems vary enormously in their degree of theoretical complexity and in their dependence on data derived from experience; and so the patterns of argument used in them, and the methods of work, will be correspondingly various. Depending on his particular experience of research, one scientist may think of 'scientific method' as the construction of models and theories, and will be concerned with the relation of theoretical entities to the real world; while another will see 'scientific method' as a series of tests of simple hypotheses converging towards a true answer to the problem. But in any scientific problem, the argument from which the final conclusions are drawn will include several sorts of inferences. One sort is *deductive*, proceeding by logical steps from assumptions to *conclusions*, as in a mathematical proof, e.g. that in a right-angled triangle, the square on the hypotenuse is equal to the sum of the squares on the two other sides. An example of this is provided by the use of geometry and trigonometry in the circle-chord theorem of the Galileo experiment. A second is *inductive*, generalizing from the properties of a sample to those of the large group from which it comes. (Such a large group is called a *class*.) For instance, it is an inductive inference when we say that *all* one-celled organisms avoid sulphuric acid, based on a study of only a few, or, that *all* rats can make hypotheses or *all* birds will shun black and yellow striped insects. You used inductive inference in generalizing the results of your experiments on rolling a ball down a table to apply to the use of *any* sphere rolling down *any* inclined plane. Some inferences are *probabilistic*, giving an estimate of the confidence that can be attached to a particular statement, as in the examples above, or in averaging from the spread of readings you obtained in the Galileo experiment. Finally, *analogical* inference, arguing by extension of accepted similarities, is used in connection with models, as when we say that *because* the molecules behave like billiard balls in such-and-such a situation therefore they must have such-and-such other properties. You used this type of inference when you assumed in the circle-chord theorem, that the rolling ball could be represented by a mathematical point, that the behaviour of the rolling ball could be extended to that of a falling body, and finally, that a large, irregular body could be treated as if it were a small sphere.

**During the course of the year's work you will find many different examples of the use of these types of inference. Note them, for at the end of the year you should be able to quote further examples derived from subsequent course units.**

What emerges from a scientist's work on a problem is not yet a 'fact'†. Although the scientist can present his conclusions *as if* it follows necessarily from hard experimental data, he and his colleagues know that it is liable to error at a multitude of points: at the production of this data, when errors in making observations can occur, in relating the data to the concepts being studied, and in the structure of argument itself. If he has worked properly, the scientist will have guarded against the inevitable tendencies to self-deception; he will have made his data as precise and

objective, and his argument as rigorous as possible. But perfection is impossible, and the result must be further tested before it can be considered as a 'fact'.

It is just because the results of scientific research cannot be perfect that the work itself is very demanding. Conceiving a genuinely new scientific problem requires an active curiosity; and following it through requires courage (for it may be an unpopular or risky line, or even simply wrong), as well as stamina. Since results can never be perfect, the scientist must constantly be exercising his judgement: is this part of the work *good enough*? There is no simple testing gauge for scientific results; and the people who will test a scientist's work are scientists like himself. If all the scientists in a field are concerned to get by with only a minimum of effort, really first-class work will become increasingly rare, and the field will become mediocre, boring and stagnant. This is why a particular sort of ethical commitment is necessary for worthwhile scientific work; and it requires leadership and morale for its maintenance.

**Section 8**

## 1.8 The achievement of scientific knowledge

Once a scientific result has been achieved it enters on a second stage of development, where the processes are *social* rather than *individual*. These may be described as *testing*, *selection* and *transformation*. Only a very small proportion of scientific results survive these processes; and it is these that make up the body of permanent results, and genuine scientific knowledge. The testing of a new result is done in two stages: first, it is scrutinized by other independent scientists before it is published in a recognized scientific journal; and it may be rejected or returned for modification. Publication as a scientific paper is the recognized form of announcing scientific results. This form of announcing results to the world emerged in the seventeenth century (before then scientists had put their results into letters to other scientists or had published them as books). Today, there are upwards of some 33 000 scientific journals in the world, often published weekly, and even the *abstracts* of articles in one field, such as chemistry, can occupy 15 000 pages a year.

If the result is published, it is subjected to selection: does anyone take notice of it? If not, it dies there and then; and this is the fate of a large proportion of the published papers in any field. The reasons for this are numerous. They include the following: first, although the work is competent, the result leads nowhere and neither suggests worthwhile new problems nor contributes useful information or techniques. An example would be a study of the number of times the letter 's' appears in the play *Hamlet* compared with *Macbeth*. Secondly, the paper uses methods that are so new and unfamiliar that no one understands it; or the results seem so strange that the work is dismissed as that of a crank. The fate of such unorthodox papers depends very much on the practices of the field to which it is offered; if it is dominated by strong men with strong ideas of what is correct and worthwhile, there is a strong risk of unconventional work being ignored. This seems to have been more prevalent in the nineteenth century than it is today. Thirdly, shortly after the appearance of the paper, another one, doing similar work more efficiently, appears. An example would be a paper describing a method for the purification of a chemical which takes 24 hours and has a 10 per cent yield of 90 per cent purity, which is followed by a paper giving a different method which takes only 10 hours, has a 70 per cent yield and a 99 per cent purity. Fourthly, when other scientists try the methods, they do not work well enough to be

worth applying to other problems, and lastly, the result is subsequently found to be wrong! In this case it might be used and cited briefly but will then quickly be forgotten.

### 1.8.1 Facts and laws

We notice that the various reasons for the non-selection of a result are concerned only with its quality; the personality, race or politics of the author is irrelevant to the assessment. This ideal is not always easy to adhere to in practice, especially when scientists are subjected to outside pressures from politicians, or when a field is split into antagonistic rival schools. But this strict ethic of scientists, a special sort of 'fair play', is just as essential to the health of science as is the individual's commitment to doing good work. If against all these obstacles a result is selected, it is then tested again through use, or the result itself may suggest further problems. If it turns out that it did not live up to its promise of usefulness, then it is quietly dropped; and it is then forgotten and dead. But if it stays alive, then quite soon it is subjected to a process of *transformation*. For as science advances, earlier results seem crude and obsolete; they must be translated into the new language. This can happen relatively rapidly, when there is a 'scientific revolution' replacing one set of concepts by another; but more commonly, it is a gradual, continuous process (the best-known example of such a major transition is, perhaps, the replacement of Newtonian gravitational theory by those of relativity by Poincaré and Einstein at the beginning of the twentieth century). If the original result cannot be translated into a useful new form, it dies at this point; but if it survives such a transformation, we can be confident that it does say something real about the world of nature; and then it is called a fact.*

A result which becomes an accepted fact need not be restricted to a statement of the properties of some particular thing (for example, the melting point of a metal). Some facts can be considered as *laws* which give a unified description of a whole range of phenomena. Some such laws can be demonstrated by simple experiments (as Galileo's law) while others have only a very indirect connection with experience and are accepted because of their power for explanation and prediction, and their coherence in unifying a mass of apparently unrelated facts. Examples of this sort are the First and Second Laws of Thermodynamics (which you will come to in Unit 5). Even such facts and laws are subject to the ravages of time. They may be revealed as crude and eventually uninteresting approximations, or the whole field of study in which they were developed may sink into oblivion.

Examples of such fields are difficult to give, because by definition they are almost forgotten (except by historians of science), but they include for instance the ramifications of the theory of the stars, Sun and Moon as moving in 'celestial spheres' around the Earth—what was called Ptolemaic astronomy. This was destroyed by the observations and theories of Copernicus, Galileo, Kepler and finally of Newton in the sixteenth and seventeenth centuries. A similar episode occurred in the nineteenth century when, because light was believed to move in waves, and waves needed to be 'in' some medium, a fluid called 'aether' which pervaded space, was postulated. You will learn more about wave motion in Units 2, 22, 28 and 29 and you will see how a totally new explanation, Einstein's theory of special relativity, made all the earlier theories about the medium of

** We should perhaps point out that some philosophers would dispute whether anything can ever be claimed to be a 'fact'. But certainly scientists at least are prepared to accept various results as facts.*

wave propagation irrelevant. A final example is provided by the attempts made by seventeenth-, eighteenth- and nineteenth-century researchers to transfuse blood between animals and man. The attempt failed, because not enough was known about the problems of immune reaction, 'rejection', and other similar bodily defence mechanisms. These could only be studied meaningfully, and the problems of transfusion overcome, in the twentieth century, as a result of advances in biology.

Facts remain in the forefront of research only for a limited time and then pass into the body of standard information used in the basic teaching of science. An example of such transformation is provided by Galileo's law. He first stated it as a property of 'naturally accelerated motion'. When Isaac Newton introduced the idea of 'force' into mechanics some fifty years after Galileo's death, the law became a 'theorem' about motions produced by certain types of force. Later, in the nineteenth century, when the law of the 'conservation of energy' (Unit 4) was applied to mechanics, the theorem was interpreted in terms of a *relation* between kinetic and potential energy in a particular system. Finally, it became a model 'experiment' used in teaching.

In this last use, such facts are shaped by the needs of teaching situations, and will retain only the faintest resemblance to their originals. What was originally a deep, difficult and perhaps obscure result, achieved in the context of advanced research, is transformed into something simple and clear, designed for easy comprehension and manipulation. Doing the experiment has shown you this in the case of Galileo's law, and you will see it again in much of the rest of this course. Thus the materials of any course in science, including this one, are the product of a lengthy process of evolution—and indeed are still evolving.

* * *

At this point you have reached the end of the main text material of Unit 1 in the Foundation Course in science.

Can you summarize here what you think are the main points and sequence of arguments in this Unit, in about half a page of writing? As a guide, look again at the list of objectives on page 8.

When you have done so—and not until—turn over the page and compare your summary with that we have made and with the conceptual diagram on pages 6 and 7.

## 1.9 Summary

This Unit, the first in the Foundation Course in science, starts by discussing the relationships between science, technology, and society. It shows how much of modern life is shaped by science and technology. This represents section 1 of the Unit. In trying to understand the nature of science, the question is asked: how did it arise, and is man's science unique? Section 2 tries to answer this by looking at the evolutionary pathway which leads to man; it shows that activities which are in some sense 'scientific' are apparent in the behaviour of many types of non-human animal. The evolutionary pathway which has led to man is one of increasing power of 'brain' and of capacity for explorative or creative behaviour. With man, these properties reach a high point which, even in primitive societies, can be seen to emerge from craft, religion and magic and extend towards what we now call science. The dawn of science is discussed in section 3. But science and scientific procedures are, as shown in sections 4 and 5, more than just craft knowledge, they are precise and objective and represent both knowledge *and* power. They require *creative work* involving the setting and solving of new problems. This is discussed, using as an example a seemingly simple experiment performed by the seventeenth-century Italian scientist, Galileo. Section 4 goes through this experiment in detail. Sections 6 and 7 ask the question 'how is a scientific result established?' and show how the procedures of making experiments and testing *hypotheses*, *laws* and *theories* have developed. Section 8 shows how results, when established, pass into the scientific literature and become 'transformed' by use into facts, knowledge—and teaching material.

## Book List

### Preparatory reading

J. D. Bernal, *Science in History*. Penguin, 1969, 4 volumes.

### Set books

J. R. Ravetz, *The Roots of Present-day Science*. Open University, 1971.
H. Rose and S. Rose, *Science and Society*. Penguin (Chapters 1–6), 1970.

### Background reading

T. S. Kuhn, *The Structure of Scientific Revolutions*. Chicago UP, 1962. (2nd edition, 1970.)
P. B. Medawar, *The Art of the Soluble*. Penguin, 1969.
J. M. Ziman, *Public Knowledge*. CUP, 1968.

# Appendix 1 (Red)

## Some examples of probability

Jones said to Smith, 'I am a very lucky man. My telephone number is 65–6237. My chances of getting this particular number were 1 in a million.'

**What was the fallacy in Jones' reasoning?**

For Jones to consider himself truly lucky, he would have needed *first* to make an hypothesis about the probability of obtaining a number in some class or classes (for instance, all digits the same, digits in sequence, a good poker hand etc.) and *then* see if such a number was assigned to him.

An American businessman got a phobia about air travel; he was afraid that he would be killed by a crash resulting from a bomb smuggled on board his plane. His firm learned from their insurance brokers that the odds against a plane carrying a smuggled bomb were 10 000 to 1. But the man was not satisfied. So he was advised to smuggle a bomb himself, for the odds against a plane carrying *two* bombs are 100 000 000 to 1.

This made him feel much more secure.

**Was he deluding himself?**

Yes, the probability quoted for two bombs only applies to the situation where there are two *independent* chance events. His own bomb was not a "chance event" in this sense. The problem could be put thus:
If a plane carries one smuggled bomb, the probability of its carrying a second one is the same as it was for the first: 1 in 10 000. So the man, carrying his bomb, was no safer than before.

A schoolboy did the experiment of 'testing the hypothesis' that $v=gt$, where $g=9.80$ m s$^{-2}$. He reported his results in the following table:

| | | | | |
|---|---|---|---|---|
| $v$ (m s$^{-1}$) | 9.80 | 19.60 | 39.20 | 78.40 |
| $t$ (s) | 1 | 2 | 4 | 8 |

He was mortified when his lab report was returned with the note: 'Failed; *Do* the experiment next time'.

**Why was the teacher dissatisfied with this perfect confirmation of the hypothesis?**

It is highly improbable that in a real experiment the results obtained would fit the "hypothesis" so perfectly and without errors due to the sort of measurement difficulties we discussed in this unit. Therefore the teacher could be reasonably sure that the student had cooked the data or perhaps had never done the experiment.

**(You have been warned!)**

**Theory of the Galileo experiment**

**(a) Proof of the 'circle-chord' theorem**

*Refer to Figure* 11

It is easy to calculate the time the ball takes to roll from C to B from the principle of conservation of energy. Suppose the ball has mass $m$. When it is at C it will have potential energy which is greater than it would have at B by the amount $mgh$, i.e. the work done against the gravitational force $mg$, in lifting the ball through a height $h$, where $g$ is the acceleration due to gravity. If it starts from rest at C and by the time it has rolled down to B, has a velocity $v$, its kinetic energy (neglecting for the moment the energy that goes into making the ball rotate) will be $\frac{1}{2}mv^2$.

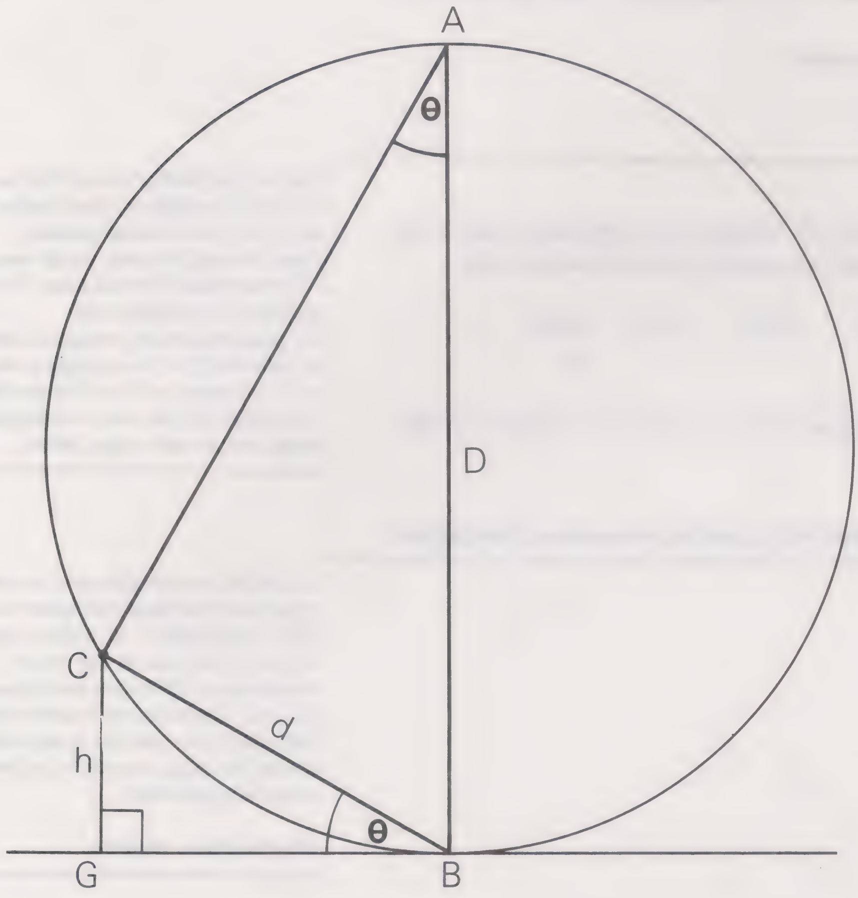



*Figure* 11

Then, by the principle of conservation of energy, the gain in kinetic energy is equal to the loss in potential energy.

That is $\frac{1}{2}mv^2 = mgh$

or $v^2 = 2gh$

$$v = \sqrt{2gh}$$

Now, since the ball is acted on by a constant force, it accelerates uniformly and so the *average* velocity, $\bar{v}$, is just half the final velocity $v$.

Thus, $\bar{v}=\frac{1}{2}v=\frac{1}{2}\sqrt{2gh}=\sqrt{gh/2}$

The time to roll the distance $d$ is then

$$t=d/\bar{v}=d/\sqrt{gh/2}=d\sqrt{2/gh}$$

But $h=d \sin \theta$ (see Fig. 11)

So $t=d\sqrt{2/gd \sin \theta}=\sqrt{2d/g \sin \theta}$ .......... (1)

and $t^2=2d/g \sin \theta$ .......... (2)

Now look at Figure 11 again. ACB is a right angle, as is ABG. It follows that the angle CAB is also $\theta$ and that

$$\sin \theta=\mathrm{CB}/\mathrm{AB}=d/D.$$

Substituting for $\sin \theta$ in equation 2

$t^2=2D/g$ .......... (3)

Thus $t$ has the same value for any chord of the circle of diameter $D$

This is Galileo's 'circle-chord theorem'.

Note that if t = 1, then, from equation 3,

$$D=g/2$$

So, *in the absence of rotation*, the diameter of the 'one-second circle' should be 4.9 m, since $g$ is about 9.8 m s$^{-2}$.

**(b) The effect of rotation**

We now take into account the energy that goes into making the ball rotate.

The *rotational* kinetic energy of a body rotating with angular velocity $\omega$ is $\frac{1}{2}I\omega^2$, where $I$ is its moment of inertia about the axis of rotation.

For a solid sphere, the moment of inertia about a diameter is $\frac{2}{5}mr^2$, where $r$ is the radius.

So the rotational kinetic energy of a rolling spherical ball is

$$\frac{1}{2}I\omega^2=\frac{1}{2} \cdot \frac{2}{5}mr^2 \cdot \omega^2$$
$$=\frac{1}{5}mv^2,$$

where $v$ is the linear velocity of the ball down the inclined plane. (Note that $r\omega$ is the linear velocity of the point of contact between the rotating ball and the inclined plane, relative to the centre of the ball. As this point of contact is at rest relative to the inclined plane, and the centre of the ball is moving with a velocity $v$ relative to the plane, it follows that $v=r\omega$.)

The *total* kinetic energy of the rolling ball is thus

$$\frac{1}{2}mv^2+\frac{1}{5}mv^2$$

and this must be equated with the potential energy $mgh$.

So $\quad (\frac{1}{2}+\frac{1}{5})mv^2 = mgh,$

or $\quad \frac{7}{10}mv^2 = mgh$

What effect will this have on the time of descent?

If you follow through the calculation as before, you will find

$$t = \sqrt{2.8d/g \sin\theta} \quad \text{.......................} \quad (4)$$

This is $\sqrt{1.4}$ times longer than the time given by equation 1, in which we neglected rotation.

So, the diameter of the 'one-second circle' you should obtain from your experiment is

$$D = g/2.8 = 3.5\text{m}.$$

You may like to verify, as an exercise, that if the moment of inertia of any body about an axis of rotation is $I$, and that body is rolled down an inclined plane in such a way as to make it rotate about that axis, then the time of descent will be

$$t = \sqrt{2(1+\alpha)d/g \sin\theta} \quad \text{..............} \quad (5)$$

where the symbols have the same meaning as before, and

$$\alpha = I/mr^2,$$

$r$ being the radius of the rolling body.
As a check, note that for a solid sphere,

$$I = \tfrac{2}{5}mr^2,$$

so $\quad \alpha = \tfrac{2}{5} = 0.4,$

and equation 5 becomes identical with equation 4.

You can use equation 5 to explain the results of the 'cylinder race' in the television programme of this Unit.

To do this, you will need to know that the moment of inertia of a hollow cylinder about its axis is

$$I = \tfrac{1}{2}m(R^2 + r^2)$$

where $R$ is the outer radius and $r$ the inner radius of the cylinder.

(See the post-broadcast section of the Broadcast Notes for this Unit's television programme for further information.)

# Appendix 3

## Glossary

ASDIC A device for detecting submarines developed in the Second World War. The word is made up of the initials of Allied Submarine Detection Investigation Committee.

FACT An assertion that is accepted as correct in the context of its use. The results of research reach the status of being facts only after the social processes of selection, testing and transformation in subsequent research and teaching.

FACTOR To increase the size of a thing by a *factor* of ten means to multiply the size by ten.

HYPOTHESIS An assertion put forward tentatively, as a guide to research rather than as a firm statement of fact.

LAW (scientific) An assertion that unifies and also serves for the explanation of a collection of facts; and is generally held to be correct within the limits of its statement.

MODEL A system, either of concepts or a physical device, whose structure and properties have important similarities to that of the state of affairs being studied. The relation between the model and its object is one of *analogy*: a similarity in some respects but not in others. A model may be advanced as an hypothesis, or used as part of a theory.

PANTOGRAPH An instrument for copying plans, diagrams, etc., on any scale.

THEORY An assertion which serves to *explain* a state of affairs; it is not claimed to be completely correct or adequate, but it is held more strongly than a mere hypothesis.

## Section 1.1

**Question 1** (*Objective* 2)

Tick to show by what factors each of the following human capabilities appear to have increased approximately over the last century?

You are reminded that the list of objectives on p. 7 has been reprinted in loose-leaf form for your convenience when doing self-assessment questions.

| | A $10^1$ | B $10^2$ | C $10^3$ | D $10^4$ | E $10^5$ | F $10^6$ | G $10^7$ | H $10^8$ | I $10^9$ | J $10^{10}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 Communication | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 2 Speed of travel | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 3 Data handling | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 4 Tapping energy sources | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| 5 Destruction by explosives | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

**Question 2** (*Objective* 3)

Place a tick in the boxes opposite those statements below which you recognize as examples of modifications caused, or being caused, to modern society by science and technology.

1 The increasing incidence of cremation ☐

2 The payment of invoices through GIRO ☐

3 The decreasing economic viability of cinemas ☐

4 The widespread wearing of mini skirts in 1970 ☐

5 The increase in pollution of the environment ☐

6 The change in laws relating to male homosexuality ☐

7 The absence of fireplaces in bedrooms of new houses ☐

8 The existence of the concept of the 'Third World' ☐

9 The layman's increase in awareness in outline, of world affairs ☐

10 The existence of the Open University ☐

11 The change in attitude to women seen smoking in public ☐

12 The increased tolerance of nudity in plays and films ☐

13 The maintenance of stockpiles of nuclear weapons ☐

14 The decrease in child mortality in Western Europe in the last 20 years ☐

**Question 3** (*Objective* 4)

> So science and technology must be seen as interdependent activities, discovery precedes invention, and invention in turn makes possible discovery. . . (Unit 1, p. 11.)

Think about this in terms of:

(a) discoveries and inventions suggesting new avenues for exploration not thought of before, and
(b) experiments or explorations conceived of, but impossible in practice until some technological advance, perhaps many years later, and in some totally different context, makes them practicable.

Illustrate your thinking by producing three paragraphs, each of which shows an example of the reciprocal interaction between science and technology. Either make up your own material entirely, or use terms from List A and List B below.

**List A**

Results of 'pure' and 'basic' research: 'science'

*concepts or discoveries*

1 radioactivity
2 mascons
3 the abnormal number of genes in Mongol children
4 cathode rays
5 age of the earth
6 expanding universe
7 atoms and nuclei
8 radio waves
9 polymerization
10 hormones
11 theories of optics
12 cosmic rays
13 viruses
14 air as a substance
15 blood groups
16 recent ideas about Stonehenge
17 electromagnetism
18 terrestrial gravitation
19 waves travelling through the earth or water
20 superconductivity
21 X-rays
22 momentum and inertia
23 light sensitivity of some chemicals
24 antibodies and antigens

**List B**

Results of 'applied' and 'developmental' research: 'technology'

*technical achievements*

1 float glass
2 contraceptive pills
3 plastics
4 microscopes
5 high speed photography
6 radiotherapy
7 atom bombs
8 computers
9 spectroscopes
10 tissue transplants
11 seismographs
12 blood transfusion
13 television
14 telescopes
15 refrigeration
16 Geiger counters
17 frozen foodstuffs
18 vacuum pumps
19 rocket fuels
20 artificial satellites and space probes
21 ultracentrifugation
22 radar
23 treatment of diabetes
24 petrol engines
25 helium balloons

**Note:** You are *not* expected to be familiar with all the concepts, discoveries and technical achievements listed above!

## Section 1.2.1

**Question 4** (*Objective* 5)

Tick to show which of the five senses, if any, is extended by which of the 14 devices or techniques listed below.

| | A<br>*Sight* | B<br>*Hearing* | C<br>*Touch* | D<br>*Taste or Smell* |
|---|---|---|---|---|
| 1. Scissors | ☐ | ☐ | ☐ | ☐ |
| 2. Binoculars | ☐ | ☐ | ☐ | ☐ |
| 3. Distillation apparatus | ☐ | ☐ | ☐ | ☐ |
| 4. Tractors | ☐ | ☐ | ☐ | ☐ |
| 5. Radio amplifiers | ☐ | ☐ | ☐ | ☐ |
| 6. Freeze drying | ☐ | ☐ | ☐ | ☐ |
| 7. Microscopes | ☐ | ☐ | ☐ | ☐ |
| 8. Pantograph† | ☐ | ☐ | ☐ | ☐ |
| 9. Oscilloscopes | ☐ | ☐ | ☐ | ☐ |
| 10. Telephone | ☐ | ☐ | ☐ | ☐ |
| 11. Washing Machine | ☐ | ☐ | ☐ | ☐ |
| 12. Asdic† | ☐ | ☐ | ☐ | ☐ |
| 13. Breathalyser | ☐ | ☐ | ☐ | ☐ |
| 14. Smoke detector | ☐ | ☐ | ☐ | ☐ |

## Sections 1.2.3, 1.2.4

**Question 5** (*Objective* 6)

A. Place a tick in the box opposite any statement which suggests strongly an action that depends on brain memory.

| | | |
|---|---|---|
| 1 | An animal consistently observed to stalk its prey from down-wind direction | ☐ |
| 2 | A chick reared by hand in isolation will open its beak when shown a good model of its parent's beak | ☐ |
| 3 | An animal jumping on receipt of an electric shock | ☐ |
| 4 | The successful training and use of tracker dogs | ☐ |
| 5 | An animal born blind seeks the maternal teat without help from the mother | ☐ |
| 6 | A man exhibiting fright on being taken into a torture chamber | ☐ |
| 7 | A breech baby may extend its leg upon sharp stimulation of the sole, contrary to the normal reaction of non-breech babies | ☐ |
| 8 | Birds reared in isolation have been observed to attempt nest-building | ☐ |

9 A person putting up an umbrella upon seeing a black sky and hearing thunder ☐

10 A person taking his finger away quickly after placing it on a hot object ☐

B. You should now be able to separate the statements you have ticked into two groups because they represent behaviour patterns suggesting two different origins. Write, in the boxes below, the two origins and the statement numbers relevant to each of them:

| | First Group | Second Group |
|---|---|---|
| **Origin** | | |
| **Statement Number** | | |

## Section 1.2

**Question 6** (*Objective* 9)

Two sets of statements are given below. Those in List A correspond to characteristic evolutionary features of man; those in List B to capabilities of man. Sort out three features from List A which distinguish man from all other organisms and place the appropriate numbers one in each of the three small boxes below. From List B select numbers which exemplify man exploiting the features selected from List A and place the appropriate List B numbers in the larger boxes, thus associating them with a specific feature (a number from List B may be used more than once).

**List A**

Characteristic evolutionary features of man

1 Growth of hair on his head
2 Communications by means of language
3 Brain/hand co-ordination
4 Possession of hand with freely moving thumb
5 Capacity to balance while walking on two feet
6 Brain size and complexity allowing advanced thinking
7 Brain-nervous system control over heart and respiratory actions (e.g. as practised by Yogis)

**List B**

Capabilities of man

1 Debating
2 Shaving
3 Running
4 Holding food in hands whilst eating
5 Philosophizing
6 Staying under water for short periods
7 Turning metal or wood on a lathe
8 Addressing a public meeting
9 Whistling
10 Telephoning
11 Jumping
12 Communication between individuals by writing
13 Development of mathematics
14 Manufacture and use of tape recorders

| | | | | | |
|---|---|---|---|---|---|
| | | | | | |

## Section 1.4

**Question 7** (*Objective* 9)

Indicate the amount of scientific and technical knowledge which you think is necessary for each of the following human skills by placing a tick in one of the boxes opposite each skill.

| | A<br>nil | B<br>slight | C<br>moderate | D<br>considerable |
|---|---|---|---|---|
| 1. Repairing a television set | ☐ | ☐ | ☐ | ☐ |
| 2. Using a washing machine | ☐ | ☐ | ☐ | ☐ |
| 3. Driving a car | ☐ | ☐ | ☐ | ☐ |
| 4. Stripping down a car engine | ☐ | ☐ | ☐ | ☐ |
| 5. Wallpapering | ☐ | ☐ | ☐ | ☐ |
| 6. Navigating a space capsule | ☐ | ☐ | ☐ | ☐ |
| 7. Cooking | ☐ | ☐ | ☐ | ☐ |
| 8. Making love | ☐ | ☐ | ☐ | ☐ |

## Sections 1.5, 1.6, 1.7

**Question 8** (*Objective* 1)

Each of the numbered definitions listed on the left below may describe one or other of the lettered terms or expressions listed on the right. Put the appropriate letter from the list on the right, in the box provided against each definition. A letter may be used more than once. Place an X in boxes where the definitions do not correspond to any of the terms or expressions.

1 A conclusion which must be accepted because the premisses upon which it is based have been accepted ☐

2 Reasoning from parallel instances ☐

3 An attempt to discover "natural laws" ☐

4 Endowment of a non-human thing with human qualities ☐

5 The application of certain rules of procedure and enquiry accepted as being scientific ☐

6 A generalizing inference from strong circumstantial evidence ☐

7 A belief derived from faith ☐

8 The development of the results of science to aid man in his attempt to control his environment ☐

9 A supposition entertained in order to account for a phenomenon ☐

A Science (several meanings)

B Technology

C Anthropomorphism

D Analogy

E Theory

F Hypothesis

G Induction

H Deduction

## Question 1

**Answers. 1, G; 2, B; 3, F; 4, C; 5, F.**

**Comment**

These figures, mentioned at the beginning of the first section of the unit, emphasize not only the enormous influence of science and technology in the last century, but also the vast increase in the *rate of change* of scientific development

## Question 2

**Answers and comments**

The following are obvious, *direct* effects of science and technology in the sense that they would never have happened otherwise: 2, 5, 13, 14.

The following are indirect effects, in the sense that they would logically be attributed to other courses, but are in effect in our civilization side-effects (or spin-out) effects of scientific developments:

3—probably mainly due to TV

7—in fact due to ready current availability of central heating systems (but Roman villas had central heating in their fireplaces, and stone water bottles)

9—due possibly to more efficient and rapid communication systems

10—The Open University was originally thought of as the 'University of the Air'—the idea was that the *main* media of teaching would be TV and radio. Clearly such an idea would not have arisen but for these technological developments.

## Question 3

You are referred to the examples given with the question.

## Question 4

**Answers and comments**

There is certainly room for argument about some of these, but one possible set of answers might be:

1 None—but you might try to argue for C.

2 Clearly A—this instrument makes distant objects appear nearer and hence more visible.

3 None—but, again you might argue that you cannot separate alcohol from a mixture of alcohol and water by using your bare fingers, but you can with a distillation apparatus—hence, perhaps C.

4 None.

5 In a superficial sense, B. You can *hear* John Arlott commenting on a cricket match at Trent Bridge even though you are in London. So in a way, a radio amplifier extends your sense of hearing.

6 None.

7 Obviously A.

8 You might have had to look this up in the glossary, or in a dictionary. If you did, you will have found that it is an instrument for copying on any scale, for instance a map, diagram or chart. Since it augments the graphic skill of a man's hand (and eye) you might say mainly C with a touch of A.

9 An oscilloscope is a highly versatile instrument, which can display in the form of a visible trace on a screen a wide variety of phenomena or processes, provided some intermediate device is used to turn the primary phenomenon or process into an electrical signal, or impulse, or a series of these. Considered in this way it is an instrument that can 'control' senses A, B and C. But perhaps its most important use is to expand *time*, that is to display a quasi-permanent image of a process that happens in a time too short for it to be observed (seen, heard or felt) directly. None of the senses A to E sense time as such.

10 Superficially B, in a similar sense to 5.

11 None, or perhaps at a pinch C. See comment 3.

12 Obviously B, as you will agree if you look it up in the glossary. It is, or was, used to detect submarines, and locate their approximate position, by sound waves.

13 Presumably D. It is supposed to be a more objective and quantitative device than a policeman's nose.

14 Likewise D. Essentially, one can leave an 'automatic' nose in an unattended building, thereby extending the range of one's sense of smell.

## Question 5

### Answers and comments

4, 6, 9, all demonstrate a dependence on brain memory; 3, 7 and 10 are reflex acts that do not depend on brain memory. 4, 6 and 9 demonstrate reliance on a *learning process*; 1, 2, 5 and 8 are examples of *innate* behaviour patterns.

## Question 6

### Answers

2, 4 and 6 in List A distinguish man from all other organisms.

Associated items from List B are:

for 2 in A: 1, 5, 8, 10, 12
for 4 in A: 2, 4, 7, 12, 14
for 6 in A: 1, 5, 8, 10, 12, 13, 14.

## Question 7

**Answers**

One could probably argue about the degree of scientific and technical knowledge required for some of these skills, but perhaps most people would agree with the options suggested below:

| | A | B | C | D |
|---|---|---|---|---|
| 1. | ☐ | ☐ | ✓ | ✓ |
| 2. | ✓ | ☐ | ☐ | ☐ |
| 3. | ✓ | ✓ | ☐ | ☐ |
| 4. | ☐ | ☐ | ✓ | ✓ |
| 5. | ✓ | ☐ | ☐ | ☐ |
| 6. | ☐ | ☐ | ✓ | ✓ |
| 7. | ✓ | ✓ | ☐ | ☐ |
| 8. | ✓ | ✓ | ☐ | ☐ |

Evidently the activities are not specified with sufficient precision to permit a definitive assignment to each one. For instance 4 would require more technical knowledge if you had to do it without the help of any sort of instruction manual (particularly if you were expected to put the engine together again afterwards). Even activity 6 might require only moderate scientific or technical knowledge if the capsule's flight were to be practically entirely controlled by the ground-based control station. This question is itself an example of the fact that to define a *skill* you have to include some statement of the *conditions* under which this task is to be performed.

## Question 8

**Answers**

1, H; 2, D; 3, A; 4, C; 5, A; 6, G; 7, X; 8, B; 9, F.

**Comment**

1 A deduction is a statement which *necessarily* follows from a proportion or premiss, irrespective of whether or not that proposition or premiss is true.

3 and 5 See page 11 of this Unit.

4 It is very common to find people endowing their pets with human attributes without the slightest justification. A more extreme example of anthropomorphism is the behaviour of a child towards his teddy bear.

6 An induction is a generalization which, although highly probable, can never be proved but only disproved. An induction is, in strict logic, indefensible. But nevertheless most creative thinking uses induction freely.

9 One makes an hypothesis to provoke one to think or experiment further. The trick used by scientists is to make a provocative hypothesis and then to design experiments aimed at disproving it. If the hypothesis is sufficiently important, continued failure by many different experiments to disprove it gradually transforms the hypothesis into a generally accepted theory. Even so, the distinction between an hypothesis and a theory is rather blurred in practice.

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